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HYPERVELOCITY IMPACT ON PRESSURIZED STRUCTURES (PART I)

by
R. F. ROLSTEN, H. H. HUNT AND J. N. WELLNITZ

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GENERAL DYNAMICS | ASTRONAUTICS

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ON

PRESSURIZED STRUCTURES

(PART I)

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GENERAL DYNAMICS | ASTRONAUTICS

FOREWORD

This report was prepared by the Materials Research Group of General Dynamics/ Astronautics in compliance with Contract AF 18(600)-1775.

The impact behavior of thin diaphragms of titanium and aluminum alloys and stainless steel, pressurized with liquid and gaseous oxygen, are discussed in the various sections of this report. Results are recorded in the tables according to experimental conditions (Table 1) as well as chronologically (Table 2). The phenomenological approach was intentionally selected so that all pertinent data could be presented before a discussion of material behavior was given in the final section of the report.

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ABSTRACT

Diaphragms of thin titanium and aluminum alloy and stainless steel sheet have been pressurized with liquid and gaseous oxygen and gaseous nitrogen, and subjected to impact from a high velocity, small steel projectile. Titanium alloys burn in the oxygen environment, but do not burn in either the sea-level air environment or pure nitrogen at pressures up to 60 psi. Films of WD-40 may inhibit the oxidation of titanium in gaseous oxygen, but have little or no effect in retarding combustion of the titanium in liquid oxygen. Although stainless steel and aluminum are relatively unreactive in the oxygen environment, these metals will burn when placed in contact with burning titanium. Moreover, all metal diaphragms under 60-psi pressure may catastrophically rip when a certain crack length or perforated area is attained.

Care should be exercised in the design of an aerospace vehicle to keep thin gauge titanium sheet away from contact with liquid or gaseous oxygen.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS, Contd.

LIST OF TABLES

1. INTRODUCTION

The greatest certainty about the hazard to aerospace vehicles from meteoric particles is the great uncertainty in the predictions. Large areas of ignorance exist and this can be attributed to the paucity of knowledge of the meteoroid environment of space and the response of materials and structures to this environment. Moreover, a large amount of the current experimental and theoretical data are subject to considerable uncertainty. Consequently, quantitative predictions derived from these crude estimates are only indicative of the orders of magnitude involved. When properly interpreted these estimates can serve as useful but not exact guides.

To further complicate the problem, aerospace vehicles have numerous areas of variable vulnerability which necessitates different shielding requirements; materials, structures, and design. In addition, the damage inflicted by the particle, material behavior, and an acceptable risk-level must be balanced against the probability of impact with a given meteoric particle. Based on this risk-level, vehicle structures can be designed which will:

a. Completely defeat all meteoric particles of a given mass and velocity.

b. Completely defeat some particles of a limited mass and velocity and permit more energetic particles to completely penetrate the structure but the puncture will be repaired via an astronaut or a self-sealant.

This will result in a shielding weight trade-off based on vehicle weight, accepted-risk level for the specific vulnerable area, and the probability of impact.

Several typical vulnerable components are:

a. Unpressurized tanks (rigid, semi-rigid, and non-rigid).

b. Pressurized compartments (manned or unmanned).

    1. Liquid.

    2. Gas.

    3. Liquid and gas.

c. Rocket motors.

d. Propellant.

e. Windows and instrumentation.

f. Astronauts.

g. Wiring, tubing, etc.

There is no doubt that impact of a meteoric particle with a space vehicle can cause intensive damage (penetration), while the meteoric particle and shear plug fragments can produce extensive damage to the components within the vehicle. In addition to these obvious hazards, other perils exist which are frequently neglected. For example, 1) a flash explosion may result from a high velocity impact with an oxygen-rich pressurized aerospace vehicle or 2) an astronaut may experience shock and/or concussion. Liquid-oxygen propellant storage tanks may explode and/or burn since they will contain both liquid and gaseous oxygen.

It has not been extablished that flash explosions or burning (rapid oxidation) results from the meteoric particle impact on an oxygen-rich pressure vessel. However, it seems quite feasible in light of the recognized materials response. This feasibility can be based on the following observed facts:

a. A considerable amount of energy is generated when a small particle impinges on a metal plate.

b. Small, unheated metal particles are pyrophoric in the normal sea level atmosphere. Oxides and nitrides can form as a result of the rapid reaction.

c. High velocity impact tests made in air with steel projectiles impinging on aluminum targets have produced oxide coatings on the target plates.

d. Small particles of projectile and target are produced during a high velocity impact. These particles will experience a temperature increase and will deflagrate in an oxygen-rich environment. Conflagration will continue as long as oxygen is in contact with any combustible material, and the heat of oxidation is sufficient to sustain the reaction. Combustible material is meant to include metal particles as well as organic materials since the product of combustion will be an oxide; i.e., oxides of metal or carbon.

e. Although gaseous oxygen is highly reactive chemically, liquid oxygen is quite inert. In fact, very few reactions are known to occur in liquid oxygen. It is believed that the low temperature (-297.4°F. or -183.0°C.) slows most reactions to a negligible rate.

It was the purpose of this program to experimentally ascertain materials compatibility with liquid and gaseous oxygen when a pressurized structure is exposed to an impulsive load. This evaluation was accomplished by subjecting a six-inch diameter by six-inch long pressurized cylinder, fabricated with replaceable diaphragms of titanium alloy (6Al-4V-Ti and 5Al-2.5Sn-Ti), aluminum alloy (2024-T3), and stainless

steel (full hard 301) to the impact from 0.097-gram to 0.211-gram steel projectiles traveling at 10,000 to 15,000 ft/sec. Impact phenomena of selected experiments were observed photographically in order to study the processes that occur.

2 EXPERIMENTAL

The explosive charge (end projection) technique was used to propel projectiles of known geometry, mass, and velocity at selected targets. The explosive charge (Figure 1) consists of plastic explosive (composition C-4) molded into a 2-inch diameter by 5-inch long cylinder with an air cavity at one end. A conical lead collet, ultimately mated to the charge cavity, is used to mount the cylindrical steel projectiles. A Number 10 blasting cap is used to initiate the explosion. Projectile velocities between 5,000 and 25,000 ft/sec are measured by breaking the three equally spaced printed circuits. The resulting signals are detected on two Tektronix model 360 oscilloscopes and recorded on polaroid film. Debris and fragments from the explosive and lead collet are prevented from contacting the test panel through the use of three blast shields (Figure 2) provided with a small diameter hole. Details of the pressurized test cylinder shown in Figure 2 are presented in the appendix.

A break circuit system is used to determine projectile velocities. Conductive grid circuit paper is placed at 3, 3-1/2, and 4 feet from the initial position of the projectile. The test panel is positioned 4-1/2 feet from the initial position of the projectile. Signals are recorded with the cameras mounted on the oscilloscopes that are shown in Figure 3. When the projectile passes through the first grid paper, a trace is started on both oscilloscopes. The trace continues until the projectile passes through the second grid paper, at which time there is a change in slope of the trace on the first oscilloscope due to the voltage drop. A second change in slope is observed on the second oscilloscope when the projectile breaks the third grid paper. Full scale on the oscilloscope corresponds to 1.0×10^{-4} second, and since the distance between the grid papers is known precisely, the average velocity of the projectile can be determined. The smoothness of the observed traces indicates essentially no "jitter" as the projectile passes through the grid papers. The flash x-ray is considered to be the most precise method of checking the velocity of a projectile. This method was used to confirm the grid measurements; accuracy was within 6 percent. A typical x-ray photograph of a projectile in flight is shown in Figure 4.

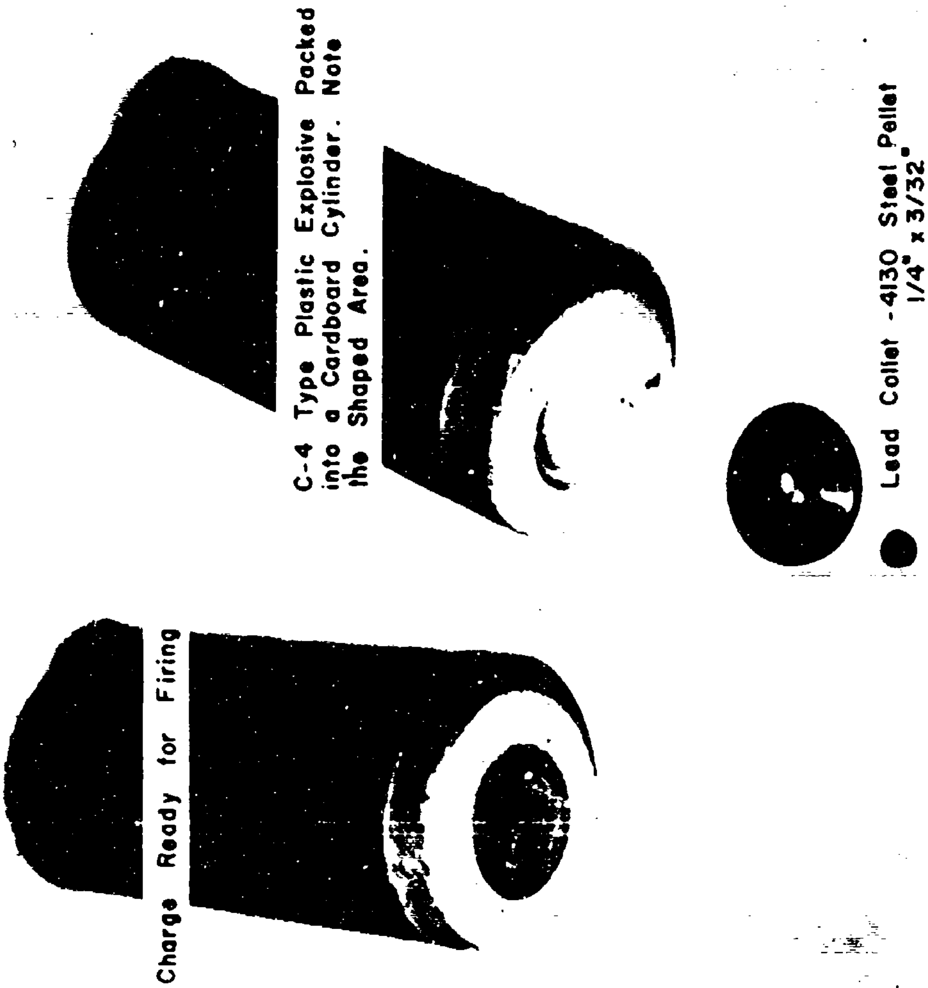


Figure 1. Explosive Driver and Projectile

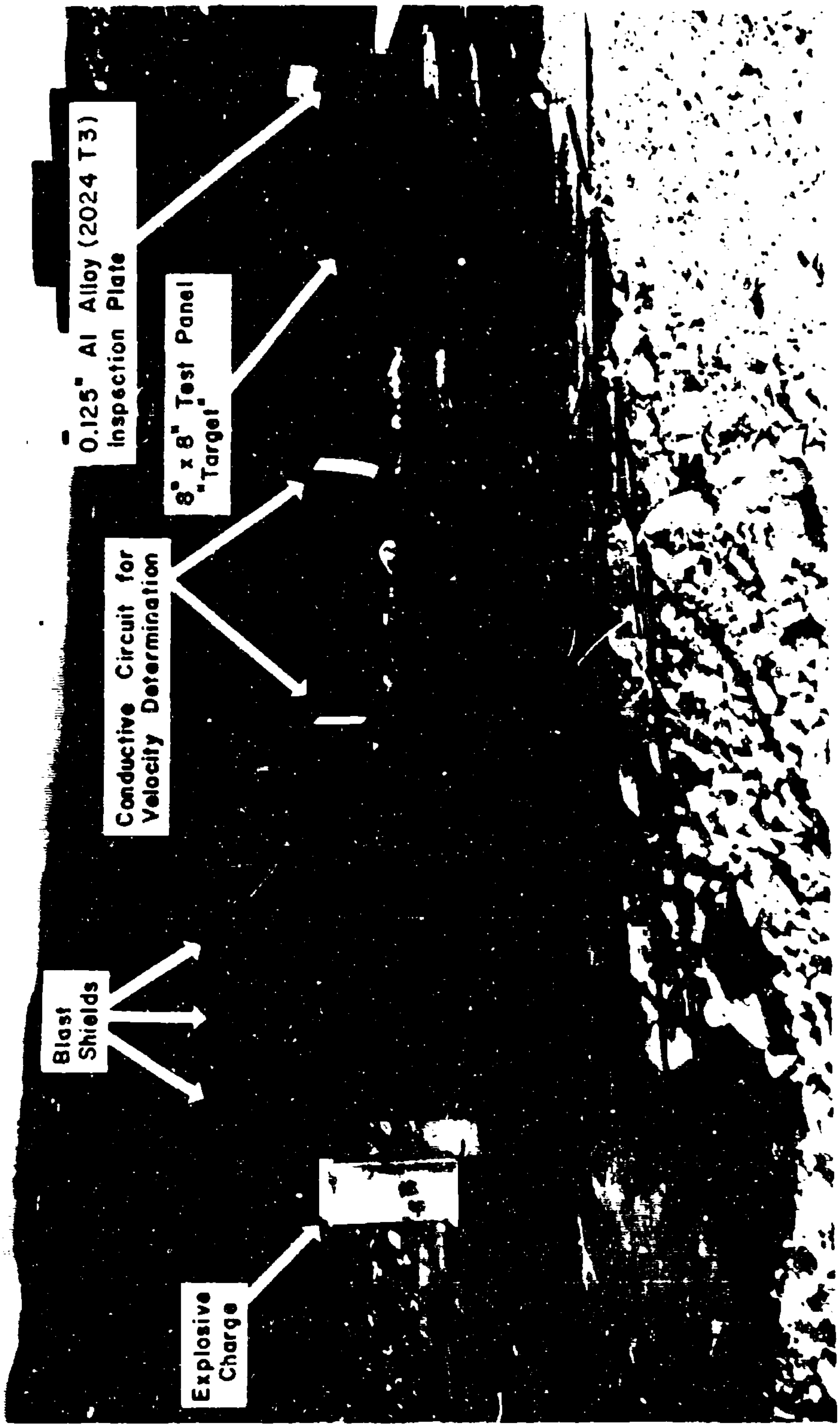


Figure 2. Test Arrangement

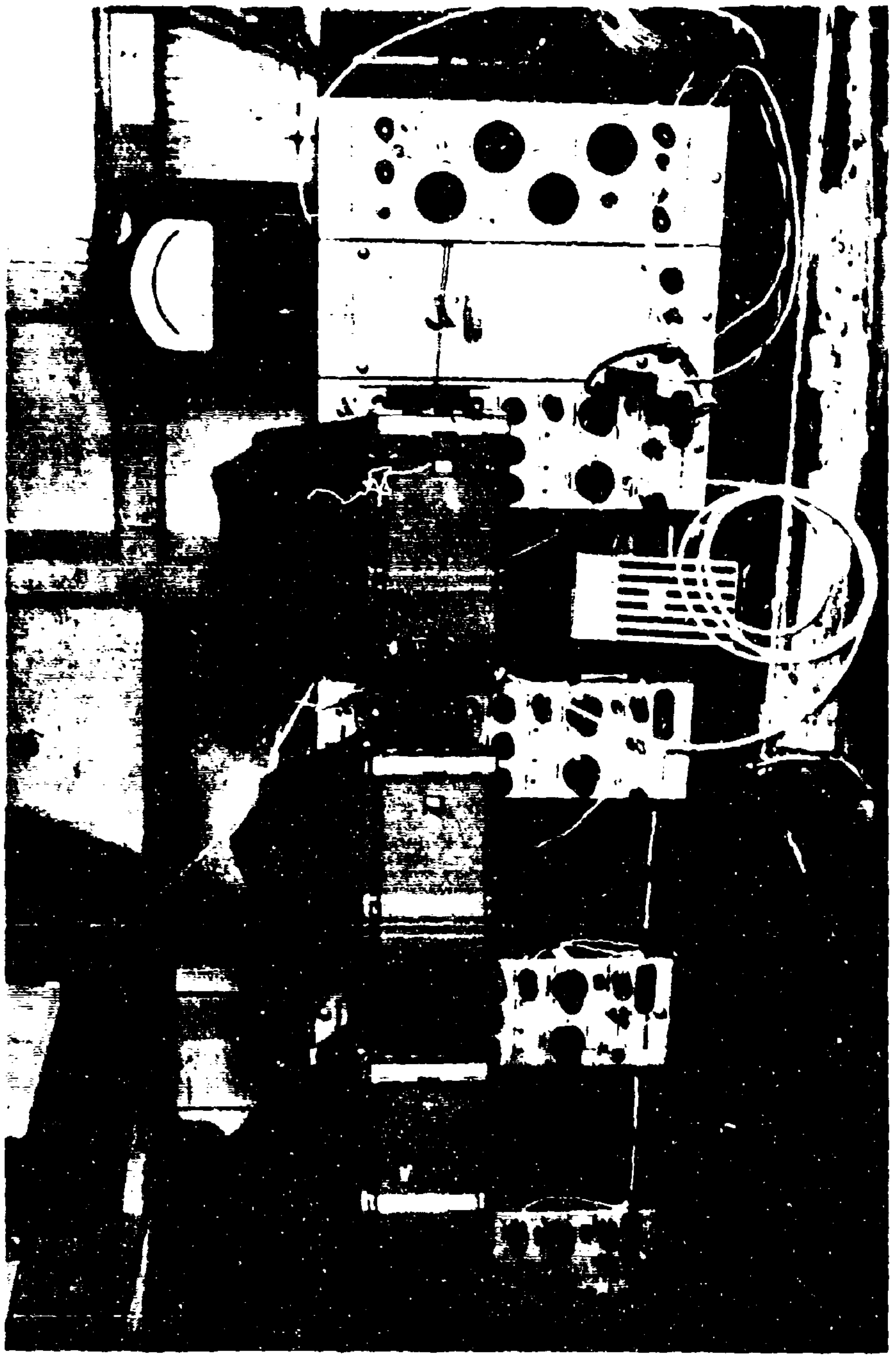


Figure 3. Velocity Measuring Equipment

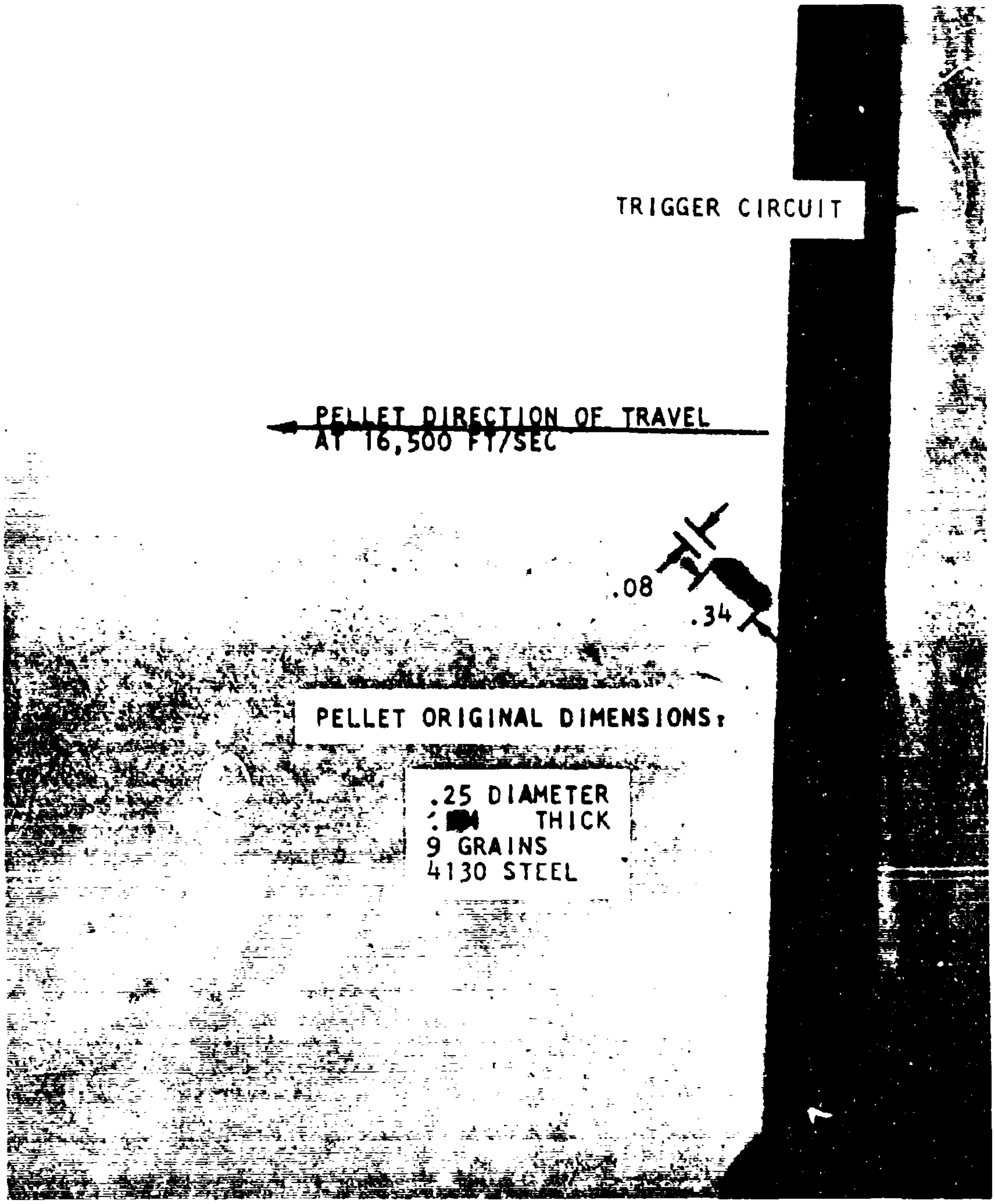


Figure 4. Flash X-Ray Photograph of a Projectile in Flight

3 IMPACT BEHAVIOR OF PRESSURIZED STRUCTURES

The data pertinent to the behavior of unpressurized and pressurized structures when subjected to impact from a high velocity steel projectile are given in Tables 1 and 2. Two sizes of steel projectile were used; 0.190-inch diameter by 0.063-inch thick weighing 0.21 gram, and 0.125-inch diameter by 0.063-inch thick weighing 0.097 gram. Velocities varied from 8900 to 15,900 ft/sec.

3.1 TITANIUM ALLOY

3.1.1 5Al-2.5Sn-Ti. Nine experiments were made (Figures 5 through 9) with the front and back diaphragms of the pressurized cylinder fabricated from untreated 5Al-2.5Sn-Ti (see Table 1 for experimental conditions). Experiments 1 and 2 were duplicate tests. That is, the 0.190-inch diameter by 0.063-inch thick steel projectile weighing 0.21 gram struck the 0.025-inch thick front and back titanium alloy diaphragms pressurized to 20 psi with gaseous oxygen. The projectile, in Experiment 1, shattered on contact with the blast shield, and produced numerous small fragments that impinged on the front diaphragm. The largest hole was 0.1 inch in diameter, and the others were less than 0.03 inch in diameter. The fragments of projectile (steel), blast shield (aluminum), and diaphragm (titanium alloy) passed through the six-inch long cylinder and pierced the rear diaphragm. A combination of the 1) energy released on particle impact with the rear diaphragm, 2) pressurized gaseous oxygen rapidly escaping through the small orifice(s), 3) low threshold for the oxidation reaction, and 4) heat generated from the exothermic reaction (Table 3) produced the burned area in the rear diaphragm, as shown in Figure 5. In Experiment 2, the projectile broke into several fragments, struck the front diaphragm at 15,900 ft/sec. and produced a large hole that was 0.33 inch in diameter (Figure 5). This hole was surrounded with partially reacted material as evidenced from the concentric rings of the different colored oxides. Inspection of the rear diaphragm shows that a large area was burned, and that the damage originated from at least three points.

A pressure of 60 psi was used in the remaining seven experiments; five of these experiments (29, 35, 37, 38, and 39) were with liquid oxygen.

Two diaphragm thicknesses (0.025-inch for Experiments 4, 37, 38, and 39; and 0.014-inch for Experiments 18, 29, and 35) and two projectile masses (0.22-gram and 0.097-gram) were used. Velocities ranged from 9,100 to 13,000 ft/sec. It should be noted that at least one of the titanium (5Al-2.5Sn-Ti) diaphragms in these seven experiments was burned (oxidized) by reaction with the oxygen environment. The quantity of material burned appears to depend on the amount of oxygen present since damage to the diaphragms at 60 psi was greater than those at 20 psi.

The front diaphragms of five test cylinders (1, 2, 4, 18, and 35) were penetrated without burning while the rear diaphragm was penetrated and burned. Four of these five cylinders were pressurized with gaseous oxygen; Experiment 35 is the only exception.

Table 1. Impact Data Summarized According to Expe

Identi-fication	Projectile Size (inches)	Projectile Weight (grams)	Impact Velocity (ft/sec.)	Type of Impact	Tank Contents	Tank Pressure (psi)	Front Diaphragm Material	Front Diaphragm Thickness (inches)	Front Diaphragm Effect	Mater
1	0.063 x 0.19	0.2105	-	Splatter	GOX	20	5Al -2.5Sn-Ti	0.025	Perforated	5Al -2.5
2	0.063 x 0.19	0.2110	15,900	Fragments	GOX	20	5Al -2.5Sn-Ti	0.025	Ignited 0.75" dia. hole	5Al -2.5
4	0.063 x 0.19	0.2190	11,600	Normal	GOX	60	5Al -2.5Sn-Ti	0.025	Punctured 0.35"	5Al -2.5
37	0.063 x 0.125	0.097	11,400	Unknown*	LOX	60	5Al -2.5Sn-Ti	0.025	Ignited	5Al -2.5
38	0.063 x 0.125	0.097	11,900	Unknown	LOX	60	5Al -2.5Sn-Ti	0.025	Ignited	5Al -2.5
39	0.063 x 0.125	0.097	9,100	Unknown	LOX	60	5Al -2.5Sn-Ti	0.025	Ignited	5Al -2.5
18	0.063 x 0.125	0.097	13,100	Edge	GOX	60	5Al -2.5Sn-Ti	0.014	Punctured 0.1 x 0.2"	5Al -2.5
29	0.063 x 0.125	0.097	12,200	Unknown	LOX	60	5Al -2.5Sn-Ti	0.014	Ignited	5Al -2.5
35	0.063 x 0.125	0.097	10,900	Edge	LOX	60	5Al -2.5Sn-Ti	0.014	Perforated 0.1 x 0.18"	5Al -2.5
3	0.063 x 0.19	0.2127	15,100	Splatter	GOX	60	6Al -4V-Ti	0.016	Perforated	6Al -4V-T
10	0.063 x 0.19	0.2020	11,200	Unknown	GOX	60	6Al -4V-Ti	0.016	Ignited	6Al -4V-T
17	0.063 x 0.125	0.097	12,500	Splatter	GOX	60	6Al -4V-Ti	0.016	Perforated 10 holes	6Al -4V-T
20	0.063 x 0.125	0.097	11,400	Normal	GOX	60	6Al -4V-Ti	0.016	Punctured 0.18"	6Al -4V-T
24	0.063 x 0.125	0.097	11,300	Fragments	GOX	60	6Al -4V-Ti	0.016	Perforated 12 holes	6Al -4V-T
28	0.063 x 0.125	0.097	12,300	Unknown	LOX	60	6Al -4V-Ti	0.016	Ignited and Blown Out	6Al -4V-T
32	0.063 x 0.125	0.097	12,500	Unknown	LOX	60	6Al -4V-Ti	0.016	Ignited	6Al -4V-T
26	0.063 x 0.125	0.097	12,200	Normal	Nitrogen Gas	60	6Al -4V-Ti	0.016	Punctured 0.26	6Al -4V-T
42	0.063 x 0.125	0.097	10,900	Normal	Air	STP	6Al -4V-Ti	0.016	Punctured 0.15"	6Al -4V-T
5	0.063 x 0.19	0.2066	< 6,000	Splatter	GOX	60	2024 T3 Al	0.016	Perforated 18 holes	2024 T3 A
11	0.063 x 0.19	0.1885	< 6,000	Splatter	GOX	60	2024 T3 Al	0.016	Perforated 6 small holes	2024 T3 A
22	0.063 x 0.125	0.097	-	Normal	GOX	60	2024 T3 Al	0.016	Punctured 0.22"	2024 T3 A
23	0.063 x 0.125	0.097	11,400	Splatter	GOX	60	2024 T3 Al	0.016	Punctured 10 holes	2024 T3 A
31	0.063 x 0.125	0.097	12,300	Normal	LOX	60	2024 T3 Al	0.016	Punctured 0.17" x 0.2"	2024 T3 A
34	0.063 x 0.125	0.097	11,600	Normal	LOX	60	2024 T3 Al	0.016	Punctured 0.15" x 0.16	2024 T3 A
36	0.063 x 0.125	0.097	11,600	Edge	LOX	60	2024 T3 Al	0.016	Punctured 0.14" x 0.2	2024 T3 A
9	0.063 x 0.19	0.2154	13,600	Normal	GOX	60	SS-301 XFH	0.010	Punctured 0.25"	SS-301 XF
13	0.063 x 0.125	0.097	11,700	Normal	GOX	60	SS-301 XFH	0.010	Punctured 0.13"	SS-301 XF
19	0.063 x 0.125	0.097	13,500	Edge	GOX	60	SS-301 XFH	0.010	Punctured 0.15"X 0.2"	SS-301 XF
21	0.063 x 0.125	0.097	11,800	Edge	GOX	60	SS-301 XFH	0.010	Punctured 0.15"X 0.3"	SS-301 XF
27	0.063 x 0.125	0.097	11,600	Normal	LOX	60	SS-301 XFH	0.010	Punctured 0.15"	SS-301 XF
30	0.063 x 0.125	0.097	8,900	Fragments	LOX	60	SS-301 XFH	0.010	Punctured	SS-301 XF
33	0.063 x 0.125	0.097	11,600	Edge	LOX	60	SS-301 XFH	0.010	Punctured 0.1" x 0.18	SS-301 XF
6	0.063 x 0.19	0.2083	12,500	Unknown	GOX	60	5Al -2.5Sn-Ti	0.025	Ignited	2024 T3 A
8	0.063 x 0.19	0.2060	Unknown	Fragments	GOX	60	2024 T3 Al	0.016	Perforated 19 holes	5Al -2.5
12	0.063 x 0.19	0.2040	Unknown	Fragments	GOX	60	6Al -4V-Ti	0.016	2 Pinholes	2024 T3 A
									Aluminum - Titanium Sandwich	
40	0.063 x 0.125	0.097	9,300	Unknown	LOX	60	2024 T3 Al 6Al -4V-Ti 2024 T3 Al	0.016 0.016 0.016	Ignited	2024 T3 A 6Al -4V-T 2024 T3 A
									Stainless Steel - Titanium Sandwich	
41	0.063 x 0.125	0.097	9,100	Unknown	LOX	60	SS-301 XFH 6Al -4V-Ti SS-301 XFH	0.010 0.016 0.010	Ignited	SS-301 X 6Al -4V-T SS-301 X
7	0.063 x 0.19	0.1985	Unknown	No Impact	GOX	60	2024 T3 Al	0.016	None	5Al -2.5
25	No Projectile	-	-	-	GOX	60	6Al -4V-Ti	0.016	None	6Al -4V-
46	0.063 x 0.125	0.097	Unknown	Missed	LOX	60	6Al -4V-Ti**	0.016	None	6Al -4V-
43	0.063 x 0.125	0.097	12,800	Unknown	LOX	60	6Al -4V-Ti**	0.016	Ignited 10 sq. in.	6Al -4V-
44	0.063 x 0.125	0.007	13,200	Normal	LOX	60	6Al -4V-Ti***	0.016	Punctured 0.15" hole	6Al -4V-
45	0.063 x 0.125	0.097	12,200	Unknown	LOX	60	6Al -4V-Ti**	0.016	Ignited, 95% burned	6Al -4V-
47	0.063 x 0.125	0.097	12,2[illegible]0	Unknown	LOX	60	6Al -4V-Ti**	0.016	Ignited, 80% burned	6Al -4V-
48	0.063 x 0.125	0.097	11,400	Normal	GOX	60	6Al -4V-Ti**	0.016	Punctured 0.15" hole	6Al -4V-
49	0.063 x 0.125	0.097	11,600	Small Fragments	GOX	60	6Al -4V-Ti***	0.016	Punctured 4 small holes (< 0.07")	6Al -4V-
50	0.063 x 0.125	0.097	11,600	Edge	GOX	60	6Al -4V-Ti**	0.016	Punctured 0.13" x 0.2	6Al -4V-
51	0.063 x 0.125	0.097	12,500	Edge	GOX	60	6Al -4V-Ti***	0.016	Punctured 0.2" x 0.25"	6Al -4V-

*Unknown, since the impact area was destroyed by oxidation.

**Both diaphragms for Nos. 45, 46, 47, 48 and 50 were coated on the outside surface only with three coats of WD 40

***Both diaphragms for Nos. 43, 44, 49 and 51 were coated on both surfaces with 3 coats of WD 40

...g to Experimental Conditions

	Rear Diaphragm			
	Material	Thickness (inches)	Effect	Remarks
	5Al -2.5Sn-Ti	0.025	Ignited	—
e	5Al -2.5Sn-Ti	0.025	Ignited	—
	5Al -2.5Sn-Ti	0.025	Ignited	Slight projectile fragmentation
	5Al -2.5Sn-Ti	0.025	Ignited 0.2" dia. hole	—
	5Al -2.5Sn-Ti	0.025	Ignited	Exploded with shower of sparks
	5Al -2.5Sn-Ti	0.025	Ignited	Exploded with evolution of yellow smoke
	5Al -2.5Sn-Ti	0.014	Ignited	—
	5Al -2.5Sn-Ti	0.014	Ignited	—
"	5Al -2.5Sn-Ti	0.014	Ignited	—
	6Al -4V-Ti	0.016	Ignited	Projectile hit baffle
	6Al -4V-Ti	0.016	Ignited	—
	6Al -4V-Ti	0.016	Ignited	—
	6Al -4V-Ti	0.016	Ignited	—
	6Al -4V-Ti	0.016	Ignited	High speed Dynafax photographs
	6Al -4V-Ti	0.016	None	Color photographs 48 frames per second
	6Al -4V-Ti	0.016	Ignited	Photographs with Hulcher camera
	6Al -4V-Ti	0.016	Perforated	19 holes
	6Al -4V-Ti	0.016	Perforated	16 holes
	2024 T3 Al	0.016	Perforated	26 impacts, 10 holes
ples	2024 T3 Al	0.016	None	—
	2024 T3 Al	0.016	Perforated with break	—
	2024 T3 Al	0.016	Perforated	11 impacts, 5 holes, high speed Dynafax photographs
2"	2024 T3 Al	0.016	Perforated	21 impacts, 13 holes, photographs with Hulcher camera
16"	2024 T3 Al	0.016	Perforated	7 holes
2"	2024 T3 Al	0.016	Perforated	20 impacts, 7 holes
	SS-301 XFH	0.010	Blew out	—
	SS-301 XFH	0.010	Perforated	35 impacts, 9 holes
"	SS-301 XFH	0.010	Perforated	34 impacts, 13 holes
"	SS-301 XFH	0.010	Perforated	32 impacts, 8 holes, high speed Dynafax photographs
	SS-301 XFH	0.010	Perforated	7 impacts, 3 holes
	SS-301 XFH	0.010	None	—
8"	SS-301 XFH	0.010	Perforated	8 holes
	2024 T3 Al	0.016	Perforated	35 impacts, 16 small holes
	5Al -2.5Sn-Ti	0.025	Ignited	—
	2024 T3 Al	0.016	1 pinhole	Projectile broke up
...dwich				
	2024 T3 Al 6Al -4V-Ti 2024 T3 Al	0.016 0.016 0.016	Ignited	—
...andwich				
	SS-301 XFH 6Al -4V-Ti SS-301 XFH	0.010 0.016 0.010	None	—
	5Al -2.5Sn-Ti	0.025	None	—
	6Al -4V-Ti	0.016	None	No projectile - charge four and one-half feet from tank
	6Al -4V-Ti**	0.016	None	—
	6Al -4V-Ti**	0.016	2 holes	—
	6Al -4V-Ti***	0.016	Ignited, 92% burned	—
	6Al -4V-Ti**	0.016	None	Tank exploded
	6Al -4V-Ti**	0.016	Ignited, 95% burned	—
	6Al -4V-Ti**	0.016	Ignited, 2 sq. in. burned	— Diaphragms for Nos. 43 to 51 were 0.016-inch alloy 6Al -4V-Ti.
ples	6Al -4V-Ti***	0.016	Punctured two 0.07" holes	—
2"	6Al -4V-Ti**	0.016	Ignited, 30% burned	—
6"	6Al -4V-Ti***	0.016	Perforated	12 impacts, 10 holes

B

Table 2. Impact Data Summarized in E

Round No. (1)	Date	Diaphragms: Front		Diaphragms: Rear		Test Conditions (2)	Projectile Velocity, (ft/sec.)	Front Diaphragm (3)
1	12-14-61	0.025"	5Aℓ-2.5Sn-Ti	0.025"	5Aℓ-2.5Sn-Ti	GOX, 20 psig, approx. 50°F	Not measured	1 hole, 0.1"; 5 holes, 0.03" dia.; not b
2	12-15-61	0.025"	5Aℓ-2.5Sn-Ti	0.025"	5Aℓ-2.5Sn-Ti	GOX, 20 psig, approx. 60°F	15,900	1 hole, 0.75"; 2 holes, 0.15" dia.; burr
3	12-15-61	0.016"	6Aℓ-4V-Ti	0.016"	6Aℓ-4V-Ti	GOX, 60 psig, approx. 60°F	15,100	7 small holes, 0.05" dia.
4	12-15-61	0.025"	5Aℓ-2.5Sn-Ti	0.025"	5Aℓ-2.5Sn-Ti	GOX, 60 psig, approx. 60°F	11,600	1 hole, 0.35"; 2 holes, 0.10" dia.
5	12-15-61	0.016"	2024 T3 Aℓ	0.016"	2024 T3 Aℓ	GOX, 60 psig, approx. 60°F	6,000	19 small holes, burned very slightly
6	12-15-61	0.025"	5Aℓ-2.5Sn-Ti	0.016"	2024 T3 Aℓ	GOX, 60 psig, approx. 60°F	12,500	25% of area burned
7	12-16-61	0.016"	2024 T3 Aℓ	0.025"	5Aℓ-2.5Sn-Ti	GOX, 60 psig, approx. 60°F	Not measured	No damage
8	12-16-61	0.016"	2024 T3 Aℓ	0.025"	5Aℓ-2.5Sn-Ti	GOX, 60 psig, approx. 60°F	Not measured	19 small holes, burned very slightly
9	12-16-61	0.010"	SS-301 XFH	0.010"	SS-301 XFH	GOX, 60 psig, approx. 60°F	13,600	1 hole, 0.25" dia.; not burned
10	12-16-61	0.016"	6Aℓ-4V-Ti	0.016"	6Aℓ-4V-Ti	GOX, 60 psig, approx. 60°F	11,200	15% of area burned
11	12-16-61	0.016"	2024 T3 Aℓ	0.016"	2024 T3 Aℓ	GOX, 60 psig, approx. 55°F	6,000	6 small holes, not burned
12	12-16-61	0.016"	6Aℓ-4V-Ti	0.016"	2024 T3 Aℓ	GOX, 60 psig, approx. 55°F	10,900	2 small holes, not burned
13	12-18-61	0.010"	SS-301 XFH	0.010"	SS-301 XFH	GOX, 60 psig, approx. 55°F	11,700	1 hole, 0.13" dia.; 1 very small hole,
14	12-18-61	None		None		-	-	-
15	12-18-61	None		None		-	-	-
16	12-18-61	None		None		-	-	-
17	12-18-61	0.016"	6Aℓ-4V-Ti	0.016"	6Aℓ-4V-Ti	GOX, 60 psig, approx. 60°F	12,500	4 holes, 0.010" dia.; 6 very small holes
18	12-18-61	0.014"	5Aℓ-2.5Sn-Ti	0.014"	5Aℓ-2.5Sn-Ti	GOX, 60 psig, approx. 60°F	13,100	1 hole, 0.1" x 0.2" dia.; not burred
19	12-18-61	0.010"	SS-301 XFH	0.010"	SS-301 XFH	GOX, 60 psig, approx. 60°F	13,500	1 hole, 0.15" x 0.20" dia.; not burned
20	12-18-61	0.016"	6Aℓ-4V-Ti	0.016"	6Aℓ-4V-Ti	GOX, 60 psig, approx. 60°F	11,400	1 hole, 0.18" dia.; not burned
21	12-20-61	0.010"	SS-301 XFH	0.010"	SS-301 XFH	GOX, 60 psig, approx. 60°F	13,500	1 hole, 0.15" x 0.30" dia.; not burned
22	12-20-61	0.016"	2024 T3 Aℓ	0.016"	2024 T3 Aℓ	GOX, 60 psig, approx. 60°F	13,500	1 hole, 0.22" dia.; not burned
23	12-20-61	0.016"	2024 T3 Aℓ	0.016"	2024 T3 Aℓ	GOX, 60 psig, approx. 60°F	11,400	2 holes, 0.10"; 3 holes, 0.05"; 5 holes, <
24	12-20-61	0.016"	6Aℓ-4V-Ti	0.016"	6Aℓ-4V-Ti	GOX, 60 psig, approx. 60°F	11,300	2 holes, 0.20" dia.; 10 small holes, bu
25	12-20-61	0.016"	6Aℓ-4V-Ti	0.016"	6Aℓ-4V-Ti	GOX, 60 psig, approx. 60°F	-	No damage
26	12-20-61	0.016"	6Aℓ-4V-Ti	0.016"	6Aℓ-4V-Ti	Gaseous Nitrogen, 60 psig, 60°F	12,200	1 hole, 0.26" dia.; 1 very small hole, n
27	12-21-61	0.010"	SS-301 XFH	0.010"	SS-301 XFH	LOX, 60 psig, -300°F	11,600	1 hole, 0.15" dia.; not burned
28	12-22-61	0.016"	6Aℓ-4V-Ti	0.016"	6Aℓ-4V-Ti	LOX, 60 psig, -300°F	12,300	Explosion on impact; 10% of area burne
29	12-22-61	0.014"	5Aℓ-2.5Sn-Ti	0.014"	5Aℓ-2.5Sn-Ti	LOX, 60 psig, -300°F	12,200	40% of area burned
30	12-22-61	0.010"	SS-301 XFH	0.010"	SS-301 XFH	LOX, 60 psig, -300°F	8,900	1 hole, 0.05" dia.; not burned
31	12-27-61	0.016"	2024 T3 Aℓ	0.016"	2024 T3 Aℓ	LOX, 60 psig, -300°F	12,300	1 hole, 0.20"; 1 hole, 0.10" dia.; not b
32	12-27-61	0.016"	6Aℓ-4V-Ti	0.016"	6Aℓ-4V-Ti	LOX, 60 psig, -300°F	12,500	80% of area burned
33	12-27-61	0.010"	SS-301 XFH	0.010"	SS-301 XFH	LOX, 60 psig, -300°F	11,600	1 hole, 0.1" x 0.18" dia.; not burned
34	12-27-61	0.016"	2024 T3 Aℓ	0.016"	2024 T3 Aℓ	LOX, 60 psig, -300°F	11,600	1 hole, 0.15" x 0.16" dia.; not burned
35	12-27-61	0.014"	5Aℓ-2.5Sn-Ti	0.014"	5Aℓ-2.5Sn-Ti	LOX, 60 psig, -300°F	10,900	1 hole, 0.10" x 0.18" dia.; not burned
36	12-27-61	0.016"	2024 T3 Aℓ	0.016"	2024 T3 Aℓ	LOX, 60 psig, -300°F	11,600	1 hole, 0.14" x 0.20" dia.; 7 small hol
37	12-28-61	0.025"	5Aℓ-2.5Sn-Ti	0.025"	5Aℓ-2.5Sn-Ti	LOX, 60 psig, -300°F	11,400	90% of area burned
38	12-28-61	0.025"	5Aℓ-2.5Sn-Ti	0.025"	5Aℓ-2.5Sn-Ti	LOX, 60 psig, -300°F	11,900	75% of area burned
39	12-28-61	0.025"	5Aℓ-2.5Sn-Ti	0.025"	5Aℓ-2.5Sn-Ti	LOX, 60 psig, -300°F	9,100	50% of area burned
40	12-28-61	0.016" 0.016" 0.016"	2024 T3 Aℓ 6Aℓ-4V-Ti 2024 T3 Aℓ	Front and Rear		LOX, 60 psig, -300°F	9,300	All diaphragms: 100% of area burned
41	12-28-61	0.010" 0.016" 0.010"	SS-301 XFH 6Aℓ-4V-Ti SS-301 XFH	Front and Rear		LOX, 60 psig, -300°F	9,100	All diaphragms: 75% of area burned
42	12-28-61	0.016"	6Aℓ-4V-Ti	0.016"	6Aℓ-4V-Ti	Air, 1 atm pressure, 65°F	10,900	1 hole, 0.15" dia.; 1 small hole, not b
43	1-9-62	0.016"	6Aℓ-4V-Ti*	0.016"	6Aℓ-4V-Ti*	LOX, 60 psig, -300°F	12,800	75% of area burned
44	1-9-62	0.016"	6Aℓ-4V-Ti*	0.016"	6Aℓ-4V-Ti*	LOX, 60 psig, -300°F	13,200	1 hole, 0.15" dia.; not burned
45	1-9-62	0.016"	6Aℓ-4V-Ti**	0.016"	6Aℓ-4V-Ti**	LOX, 60 psig, -300°F	12,200	Explosion ruptured diaphragm; 95% of
46	1-9-62	0.016"	6Aℓ-4V-Ti**	0.016"	6Aℓ-4V-Ti**	LOX, 60 psig, -300°F	9,200	Not hit
47	1-9-62	0.016"	6Aℓ-4V-Ti**	0.016"	6Aℓ-4V-Ti**	LOX, 60 psig, -300°F	12,200	85% of area burned
48	1-9-62	0.016"	6Aℓ-4V-Ti**	0.016"	6Aℓ-4V-Ti**	GOX, 60 psig, 60°F	11,400	1 hole, 0.15" dia.; not burned
49	1-9-62	0.016"	6Aℓ-4V-Ti*	0.016"	6Aℓ-4V-Ti*	GOX, 60 psig, 60°F	11,600	4 small holes, not burned
50	1-10-62	0.016"	6Aℓ-4V-Ti**	0.016"	6Aℓ-4V-Ti**	GOX, 60 psig, 60°F	11,600	1 hole, 0.13" x 0.2" dia.; not burned
51	1-10-62	0.016"	6Aℓ-4V-Ti*	0.016"	6Aℓ-4V-Ti*	GOX, 60 psig, 60°F	12,500	1 hole, 0.20" x 0.25" dia.; not burned

(1) Round No. 14, 15, 16 were accuracy shots, only. Test tank was not used.

(2) For tests 1 through 12 the projectile fired was 3/16" diameter x 1/16" thick steel, 0.21 grams. For all other tests the projectile was 1/8" diameter x 1/16" thick steel, 0.097-grar The propellant used for all tests was 400 grams of C-4 explosive.

(3) Burned area was estimated.

* Both diaphragms for Nos. 43, 44, 49 and 51 were coated on both surfaces with 3 coats of WD 40.

** Both diaphragms for Nos. 45, 46, 47, 48 and 50 were coated on the outside surface only with three coats of WD 40.

A

Summarized in Experimental Number Sequence

Experimental Results		
Front Diaphragm(3)	Rear Diaphragm(3)	Remarks
1"; 5 holes, 0.03" dia.; not burned	15% of area burned	Not a direct hit; projectile hit the baffle and particles sprayed front diaphragm.
75"; 2 holes, 0.15" dia.; burned slightly	35% of area burned	Slight projectile fragmentation on acceleration.
les, 0.05" dia.	35% of area burned	Not a direct hit; projectile hit the baffle and particles sprayed front diaphragm.
35"; 2 holes, 0.10" dia.	40% of area burned	Slight projectile fragmentation on acceleration.
oles, burned very slightly	26 impacts, 10 small holes, burned very slightly	Projectile fragmented before hitting front diaphragm.
burned	1 hole, 0.15"; 2 holes, 0.05"; 13 holes, < 0.05" dia.	35 impacts on rear diaphragm.
	No damage	Pellet hit baffle, but not front diaphragm. Tank remained pressurized after blast.
les, burned very slightly	45% of area burned	Same tank and diaphragms used in Round No. 7.
5" dia.; not burned	Entire diaphragm ruptured, not burned	Normal impact of projectile.
burned	15% of area burned	-
les, not burned	No damage	Projectile fragmented before hitting front diaphragm.
les, not burned	1 small hole, not burned	Projectile fragmented before hitting front diaphragm.
3" dia.; 1 very small hole, not burned	35 impacts, 9 holes, 0.10" dia.	-
	-	Shot was not a test; see note (1).
	-	Shot was not a test; see note (1).
	-	Shot was not a test; see note (1).
010" dia.; 6 very small holes, not burned	65% of area burned	Projectile fragmented before hitting front diaphragm.
" x 0.2" dia.; not burned	90% of area burned	Projectile hit on edge and formed a single elliptical hole in front diaphragm.
6" x 0.20" dia.; not burned	34 impacts, 13 very small holes, not burned	Projectile hit on edge and formed a single elliptical hole in front diaphragm.
8" dia.; not burned	75% of area burned	Normal impact of projectile.
5" x 0.30" dia.; not burned	32 impacts, 8 small holes, not burned	Same results as in Rounds 18 and 19. High speed photographs taken (Dynafax).
2" dia.; not burned	At least 10 small holes, not burned	Normal projectile impact. Damage so extensive as to prevent counting of holes.
10"; 3 holes, 0.05"; 5 holes, < 0.05", not burned	1 hole, 0.20"; 4 holes, 0.05" dia.; burned very slightly	11 impacts on rear diaphragm. High speed photographs (Dynafax).
.20" dia.; 10 small holes, burned very slightly.	80% of area burned	Projectile fragmented before hitting diaphragm. High speed photographs (Dynafax).
	No damage	Explosive intentionally fired without projectile. Tank remained pressurized.
6" dia.; 1 very small hole, not burned	2 holes, 0.10" dia.; 17 very small holes	Same tank and diaphragms used in experiment 25. Normal impact of projectile
15" dia.; not burned	7 impacts; 1 hole, 0.15" dia.; 2 small holes not burned	Normal impact of projectile.
on impact; 10% of area burned	No damage	Color photographs taken at 48 frames per second.
burned	65% of area burned	Projectile fragmented on acceleration.
05" dia.; not burned	Not damaged	Projectile hit baffle and fragmented before hitting front diaphragm.
20"; 1 hole, 0.10" dia.; not burned	1 hole, 0.15" dia., 12 small holes, burned very slightly	21 impacts on rear diaphragm. Photographs taken with Hulcher camera.
burned	90% of area burned	Photographs taken with Hulcher camera.
1" x 0.18" dia.; not burned	8 small holes, not burned	Projectile hit on edge and formed a single elliptical hole in front diaphragm.
5" x 0.16" dia.; not burned	1 hole, 0.10" dia.; 6 small holes, burned very slightly	Normal impact of projectile.
0" x 0.18" dia.; not burned	75% of area burned	Projectile hit on edge and formed a single elliptical hole in front diaphragm.
4" x 0.20" dia.; 7 small holes, not burned	1 hole, 0.10" dia.; 7 small holes, burned very slightly	-
burned	1 hole, 0.2" dia.; burned very slightly	-
burned	95% of area burned	Cylinder appeared to explode with a shower of incandescent material.
burned	95% of area burned	Cylinder appeared to explode 0.1 sec. after impact, evolution of yellow cloud of smoke
agms: 100% of area burned	All diaphragms: 90% of area burned	Each panel consisted of a sandwich: Al + Ti + Al.
agms: 75% of area burned	No damage	Each panel consisted of a sandwich: SS + Ti + SS.
15" dia.; 1 small hole, not burned	1 hole, 0.10" dia.; 14 small holes, not burned	Normal impact of projectile.
burned	1 hole, 0.50"; 1 hole, 0.10" dia.; burned slightly	-
15" dia.; not burned	90% of area burned	Normal impact of projectile.
ruptured diaphragm; 95% of area burned	3 dents in diaphragm, but not pierced	-
	Not hit	Projectile hit baffle, did not hit front diaphragm. Tank remained pressurized.
burned	95% of area burned	-
15" dia., not burned	10% of area burned	Normal impact of projectile
les, not burned	2 small holes, not burned	Projectile fragmented before hitting target.
13" x 0.2" dia.; not burned	30% of area burned	Projectile hit on edge and formed a single elliptical hole in front diaphragm.
20" x 0.25" dia., not burned	1 hole, 0.30"; 1 hole, 0.20" dia.; not burned	Projectile hit on edge and formed a single elliptical hole in front diaphragm.

1/16" thick steel, 0.097-gram

AE62-0207
31 January 1962

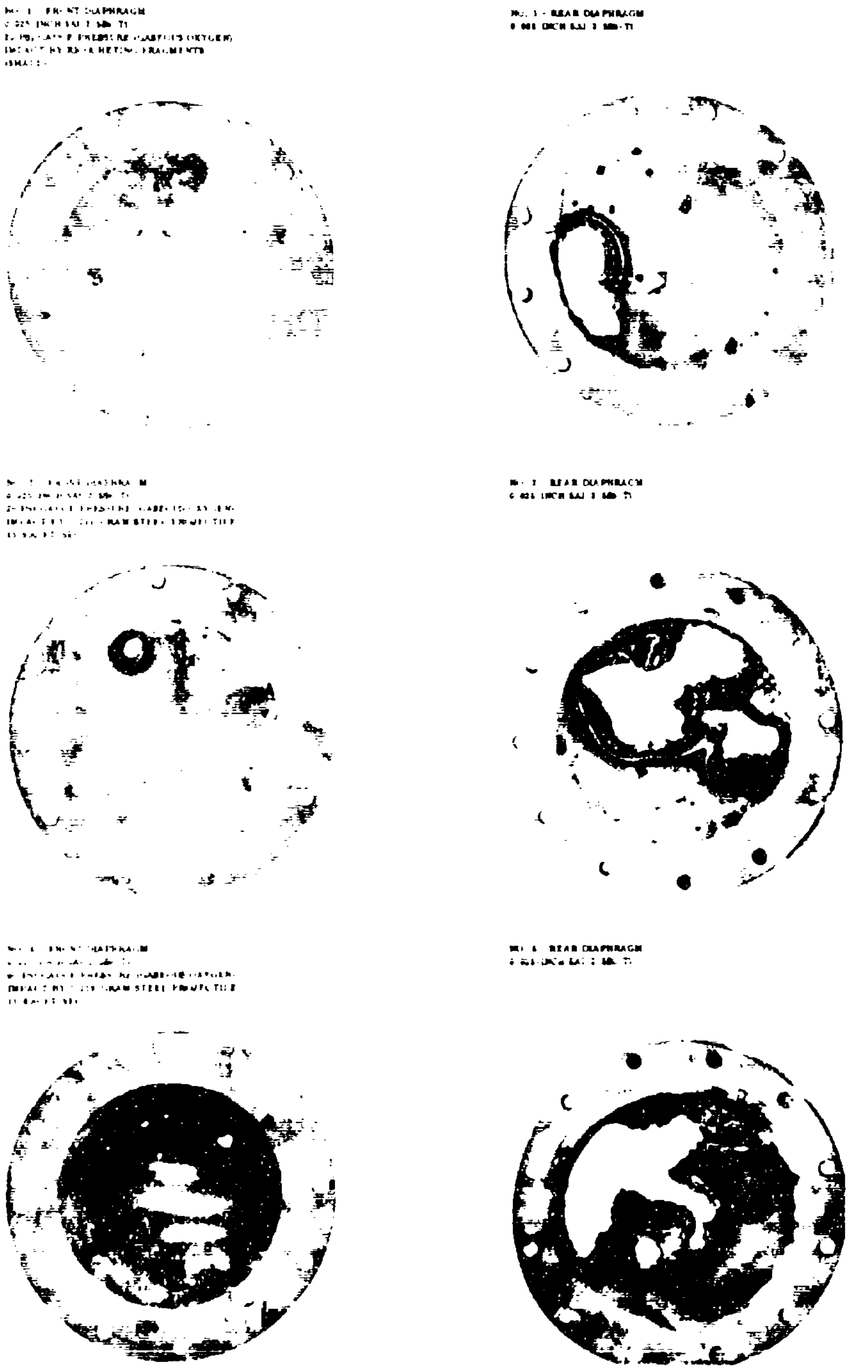


Figure 5. Test Panels 1, 2, and 4. (5Al-2.5Sn-Ti; 0.21-Gram Projectile; 60-psi Pressure)

Table 3. The Heats and Free Energies of Formation for Titanium Oxides.

OXIDES	$-\Delta H_{f, 298°K}$ (kcal/mole)	$-\Delta F_{f, 298°K}$ (kcal/mole)
$Ti(s, \alpha) + \frac{1}{2} O_2(g) \rightarrow TiO(s, \alpha)$	123.9	117.0
$2\ Ti(s, \alpha) + \frac{3}{2} O_2(g) \rightarrow Ti_2O_3(s, \alpha)$	362.9	342.4
$3\ Ti(s, \alpha) + \frac{5}{2} O_2(g) \rightarrow Ti_3O_5(s, \alpha)$	586.7	553.1
$Ti(s, \alpha) + O_2(g) \rightarrow TiO_2(s, \text{rutile})$	225.5	212.4

since liquid oxygen was used. The rear diaphragm of this test panel, still on the test stand, can be seen in Figure 8. The bottom section of the stainless steel flange is coated with globules of the titanium alloy that melted during the oxidation reaction.

Damage inflicted to five test panels pressurized with liquid oxygen is shown in Figures 6 and 7. The damage is quite severe, and both diaphragms in three of the test panels (29, 38, and 39) were burned extensively. An explosion occurred about 0.1 second after the 0.097-gram projectile, traveling at 11,900 ft/sec, struck test panel 38. This explosion resulted in the shower of incandescent titanium alloy particles that can be seen (exposure time of 1/125 second) in Figure 9.

The reaction(s) occurring between titanium and oxygen (Experiment 29) as a result of the 0.097-gram, 12,200 ft/sec steel projectile striking the 60-psi pressurized cylinder can be seen in Figure 10. These sequence photographs were selected at a definite time after the initial impact in order to show the effect. Both 0.014-inch diaphragms (5Al-2.5Sn-Ti) were penetrated. Frame A shows the titanium of the front diaphragm burning, and liquid metal from the rear diaphragm flowing over the edge of the stainless steel flange. The reaction increases, as seen from the shower of sparks in Frames B and C. Incandescent liquid metal can be seen in Frame D (6.146 seconds after impact) as it flows over the edge of the stainless steel flange at the front of the test panel. Forty percent of the exposed area of the front diaphragm, and 65 percent of the rear diaphragm were burned as seen in the appropriate photograph of Figure 6.

3.1.2 <u>6Al-4V-Ti.</u> Seven experiments were made with both diaphragms of 0.016-inch thick titanium alloy (6Al-4V-Ti) pressurized to 60 psi. The projectile mass in two experiments (3 and 10) was 0.21 gram, and was 0.097 gram in the remaining five experiments (17, 20, 24, 28, and 32). Gaseous oxygen was used in five experiments and liquid oxygen in two experiments (28 and 32).

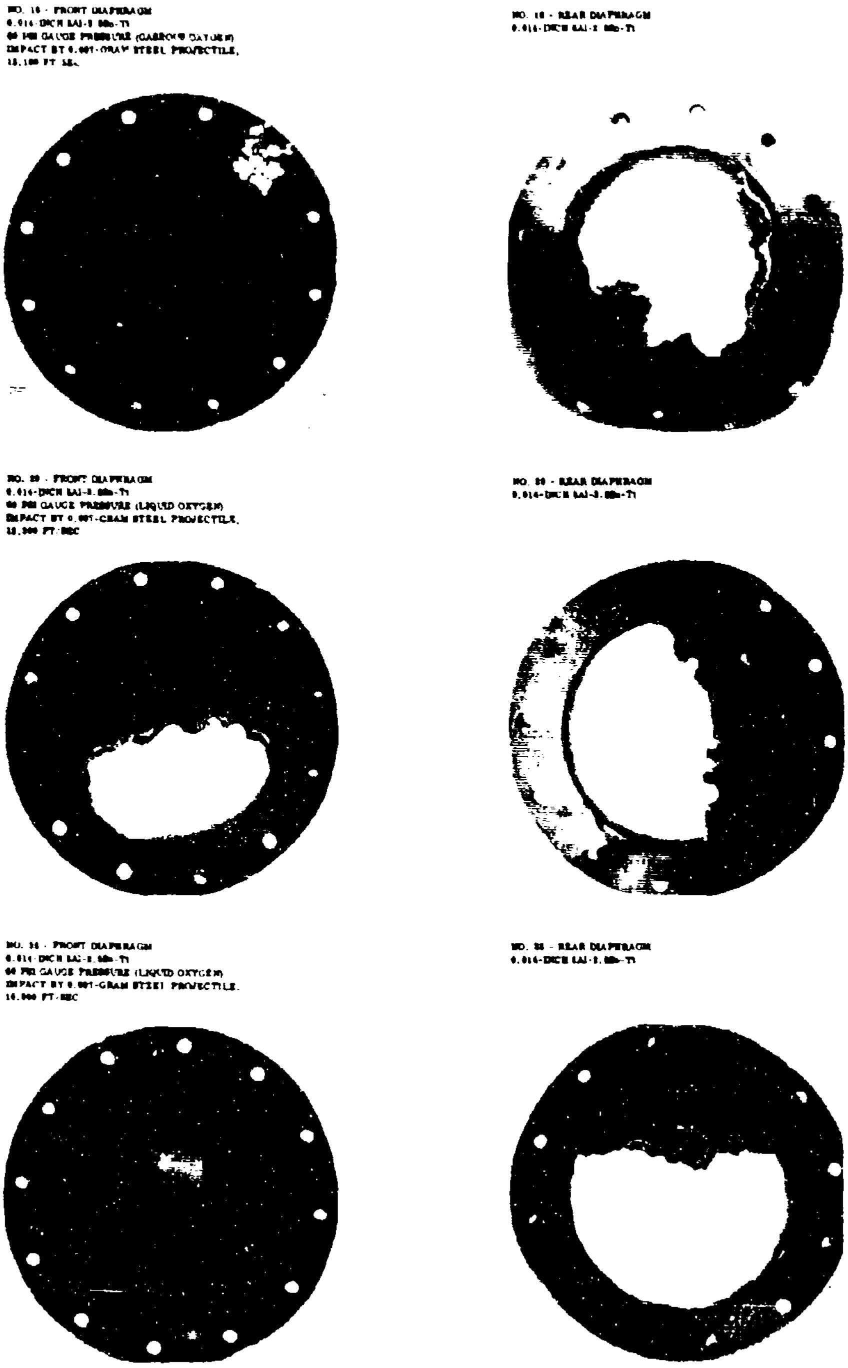


Figure 6. Test Panels 18, 29, and 35 (5Al-2.5Sn-Ti; 0.097-Gram Projectile; 60-psi Pressure)

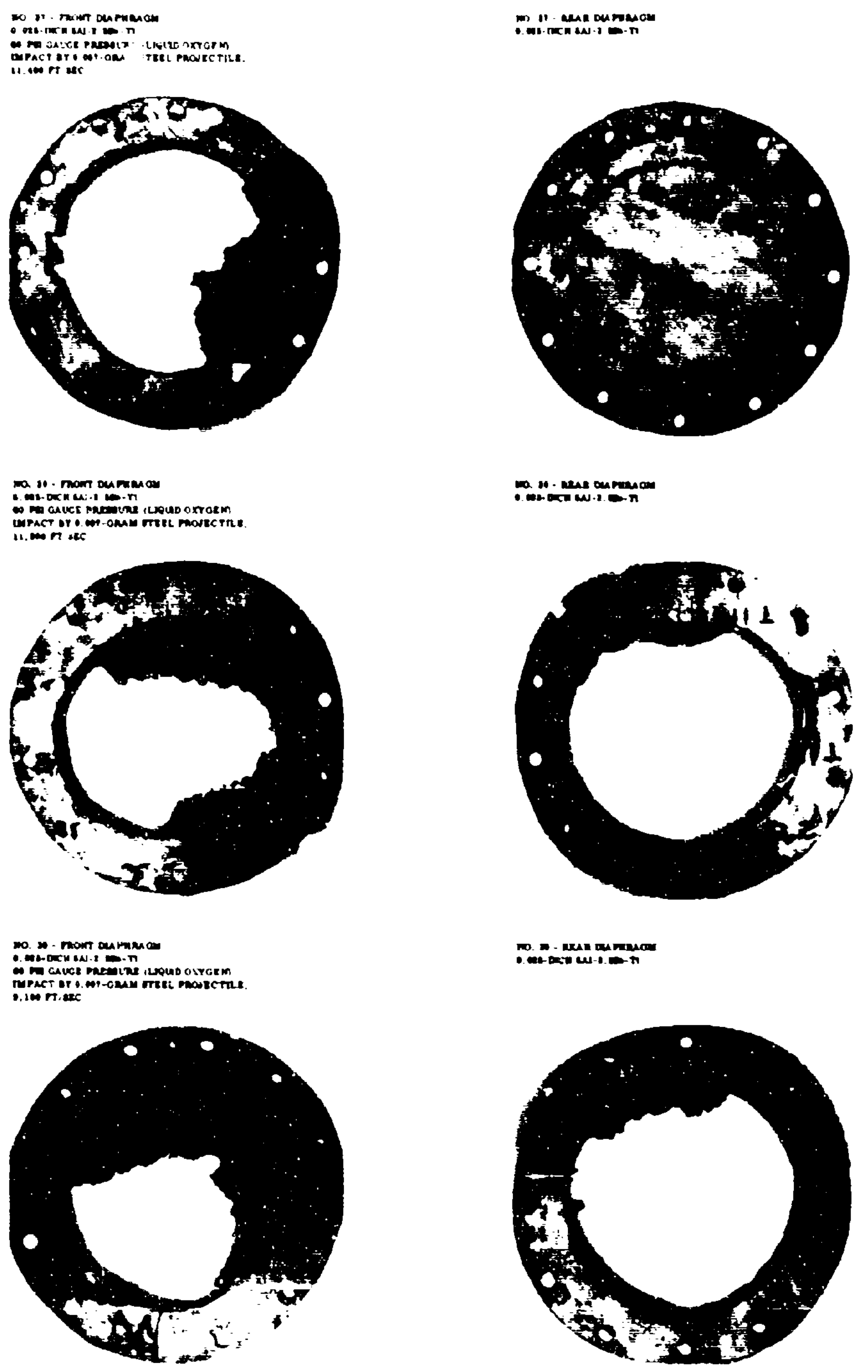


Figure 7. Test Panels 37, 38, and 39 (5Al-2.5Sn-Ti; 0.097-Gram Projectile; 60-psi Liquid Oxygen)

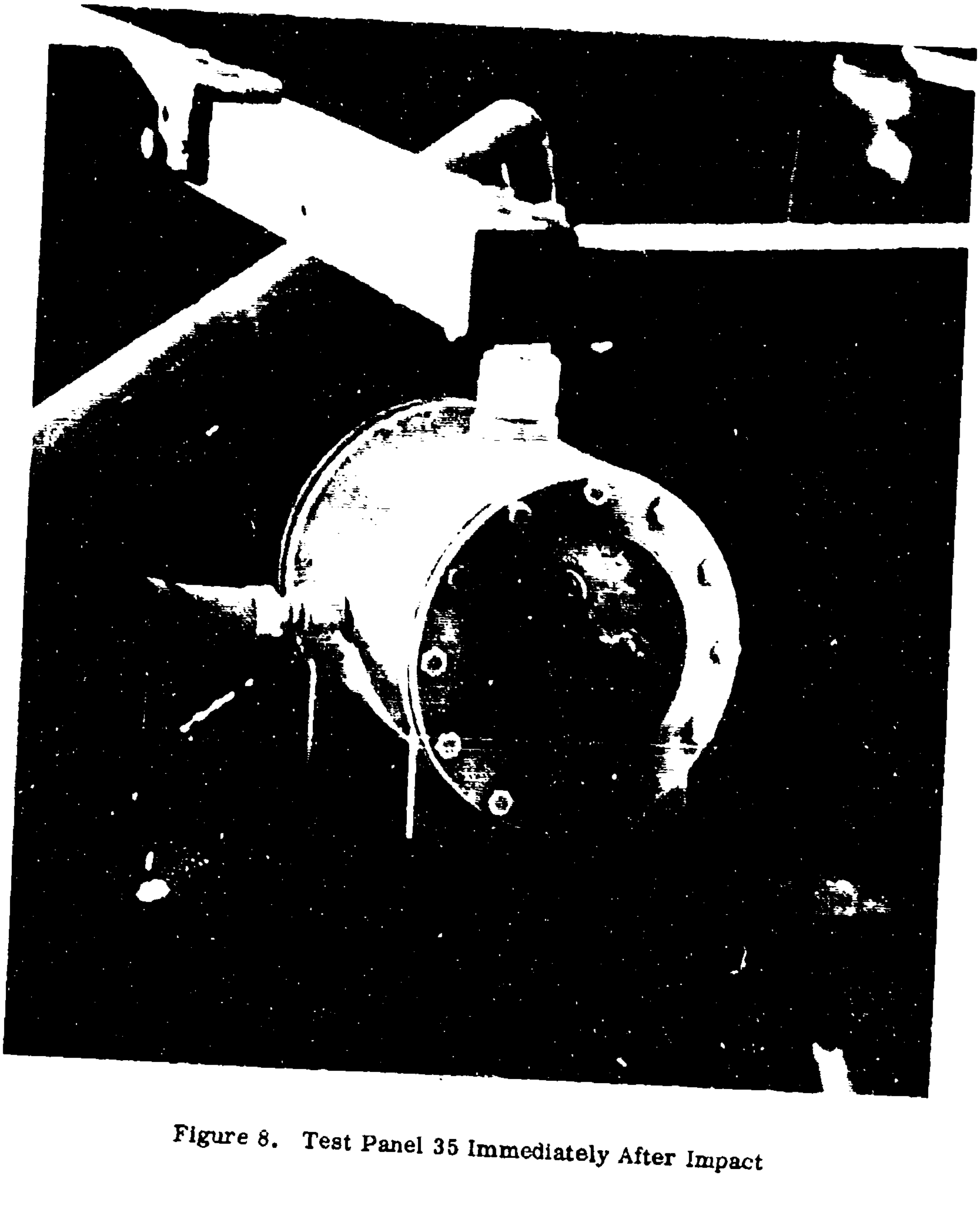


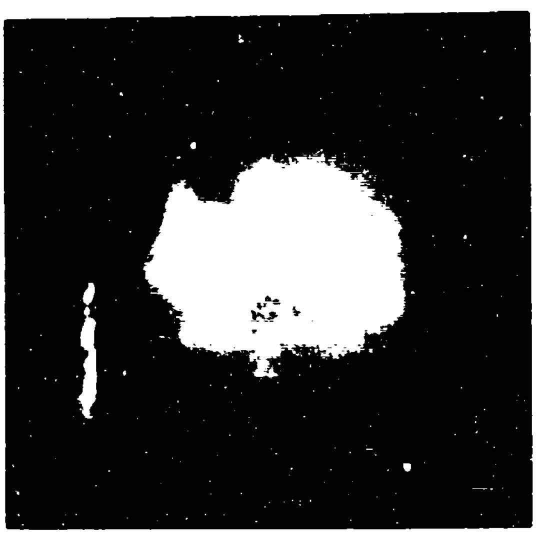
Figure 8. Test Panel 35 Immediately After Impact

Figure 9. Panel 38 After Impact (0.1-Second)

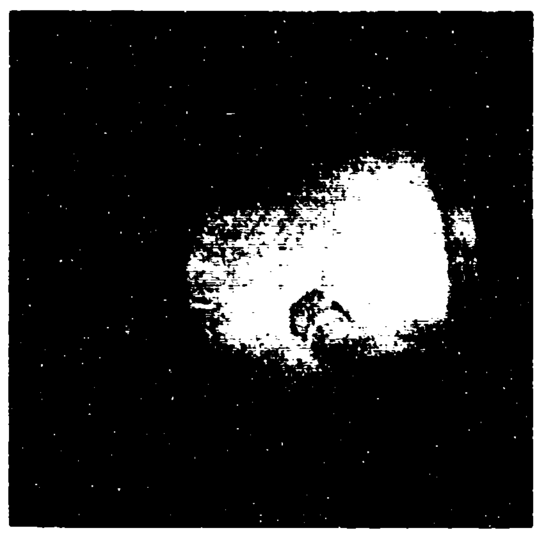
PROJECTILE →

FRAME A. 2.44 SECONDS AFTER IMPACT. BOTH DIAPHRAGMS ARE BURNING. NOTE LIQUID FLOWING DOWN REAR DIAPHRAGM AND OVER STAINLESS STEEL FLANGE.

FRAME B. 2.875 SECONDS AFTER IMPACT. BOTH DIAPHRAGMS ARE BURNING RAPIDLY IN A SHOWER OF TITANIUM SPARKS.



FRAME C. 4.06 SECONDS AFTER IMPACT.



FRAME D. 6.14 SECONDS AFTER IMPACT. LIQUID FLOWING DOWN FACE OF DIAPHRAGM AND OVER THE STAINLESS STEEL FLANGE.

Figure 10. Test Panel 29 Reacting After Impact (Titanium Diaphragm Pressurized with Liquid Oxygen)

The projectile in Experiment 3 struck the blast shield and shattered; the ricocheting particles produced seven very small holes (0.05-inch diameter) in the front diaphragm. Approximately 35 percent of the exposed area of the rear diaphragm was burned. Experiment 10 was a duplicate of Experiment 3. The 0.2020-gram projectile traveling at 11,200 ft/sec struck the 0.016-inch diaphragm pressurized to 60 psi with gaseous oxygen. About 15 percent of the front and the back diaphragms were burned (Figure 11). Test panels 17, 20, and 24 (Figure 11) were pressurized with gaseous oxygen to 60 psi, and subjected to impact from the 0.097-gram projectile. The front diaphragm in four experiments was penetrated and did not burn, but the rear diaphragms were burned. High speed photographs of Experiment 24 were taken with the Beckman-Whitley Dynafax Camera at the rate of 25,600 frames-per-second and the sequence photographs are shown in Figure 12. The camera was focused on the rear diaphragm.

The front diaphragm of test panel 28 ruptured from the impact of the 0.097-gram projectile traveling at 12,300 ft/sec. Frame A (Figure 13) shows the flap of titanium ripped from the front diaphragm as the liquid oxygen pressure was released. This flap of metal burned in the oxygen atmosphere, and the reaction can be seen in Frame B, which was taken 2.67 seconds after the impact. The rear diaphragm was not penetrated or damaged.

Experiment 32 was a duplicate of Experiment 28, but the results were quite different. The front diaphragm (Experiment 28) was penetrated and ruptured, with no damage to the rear diaphragm as seen in Figure 13. However, in Experiment 32 there was no secondary* explosion, and both diaphragms were penetrated and burned; 60 percent and 90 percent burned area of the front and rear diaphragms, respectively (Figure 14). Sequence photographs shown in Figure 14 were taken with a 70 mm Hulcher camera at the rate of 25 frames-per-second. Frame 1 (Figure 14) shows the test arrangement just prior to the detonation of the shaped explosive driver. Impact from the projectile resulted in the penetration of both diaphragms with the production of a cascade of incandescent titanium particles from the rear diaphragm, as seen in the sequence. The black fragments in the background are chunks of wood that were used to support and align the shaped explosive charge.

The greatest release of energy is observed when the rear diaphragm of titanium alloy is penetrated and starts to oxidize, as evidenced by the light intensity in Frame 2 (Figure 14). Burning subsides after the initial reaction and seems to be about constant from Frames 3 through 10. After 0.40 second (Frame 11), the intensity increases as the front diaphragm starts to react violently with the eruption of the shower of incandescent particles. These particles move in both directions from the front diaphragm, i.e., some particles leave the front diaphragm, pass through the test cylinder and out the rear of the cylinder, since the back diaphragm has already been burned. The oxidation reaction continues through Frame 16 (0.60 second after impact), the end of the photographic sequence.

*Detonation of the explosive charge is considered the primary explosion. Detonation due to the reactivity of metal (in this case, titanium) with oxygen is a secondary explosion.

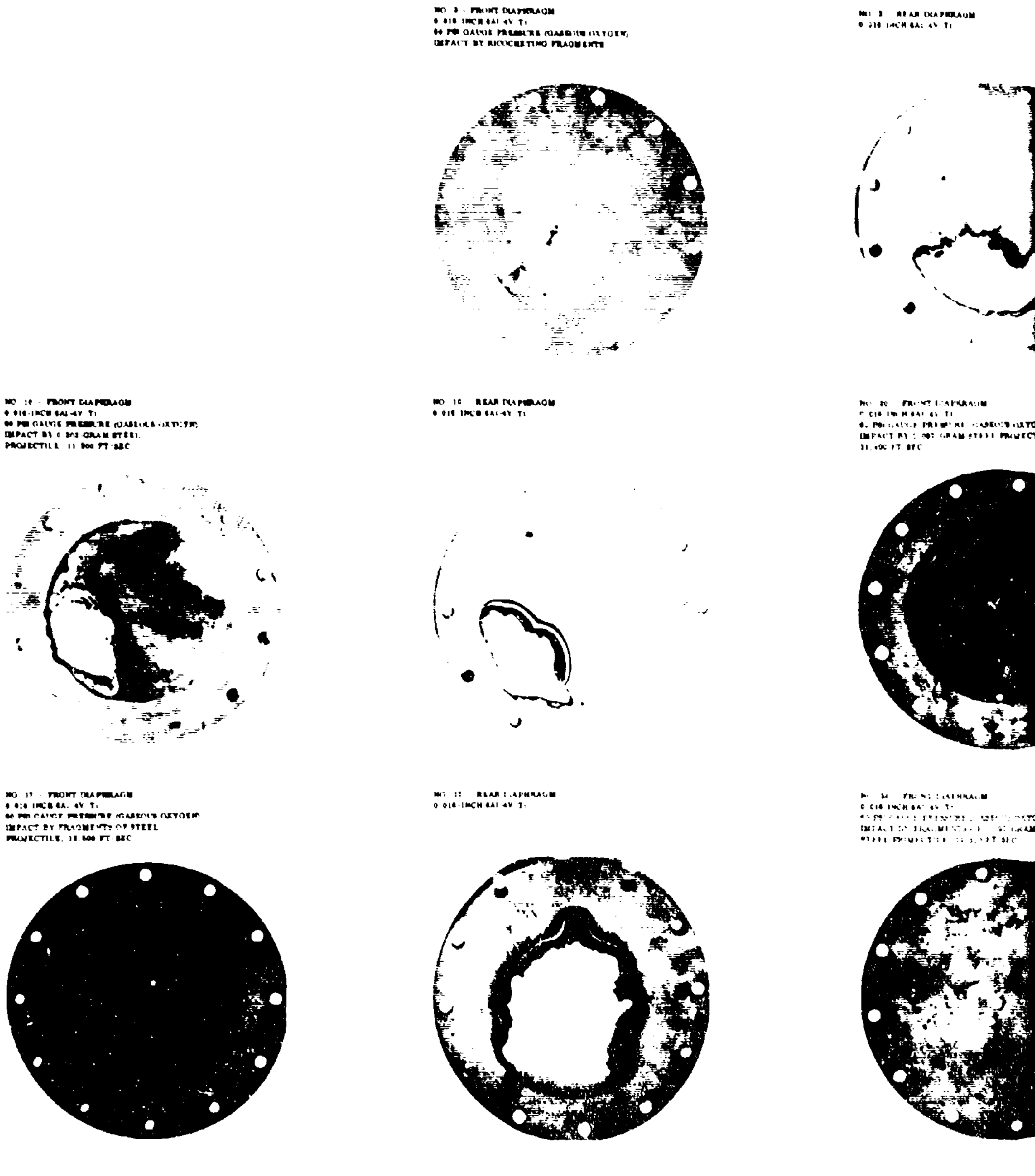
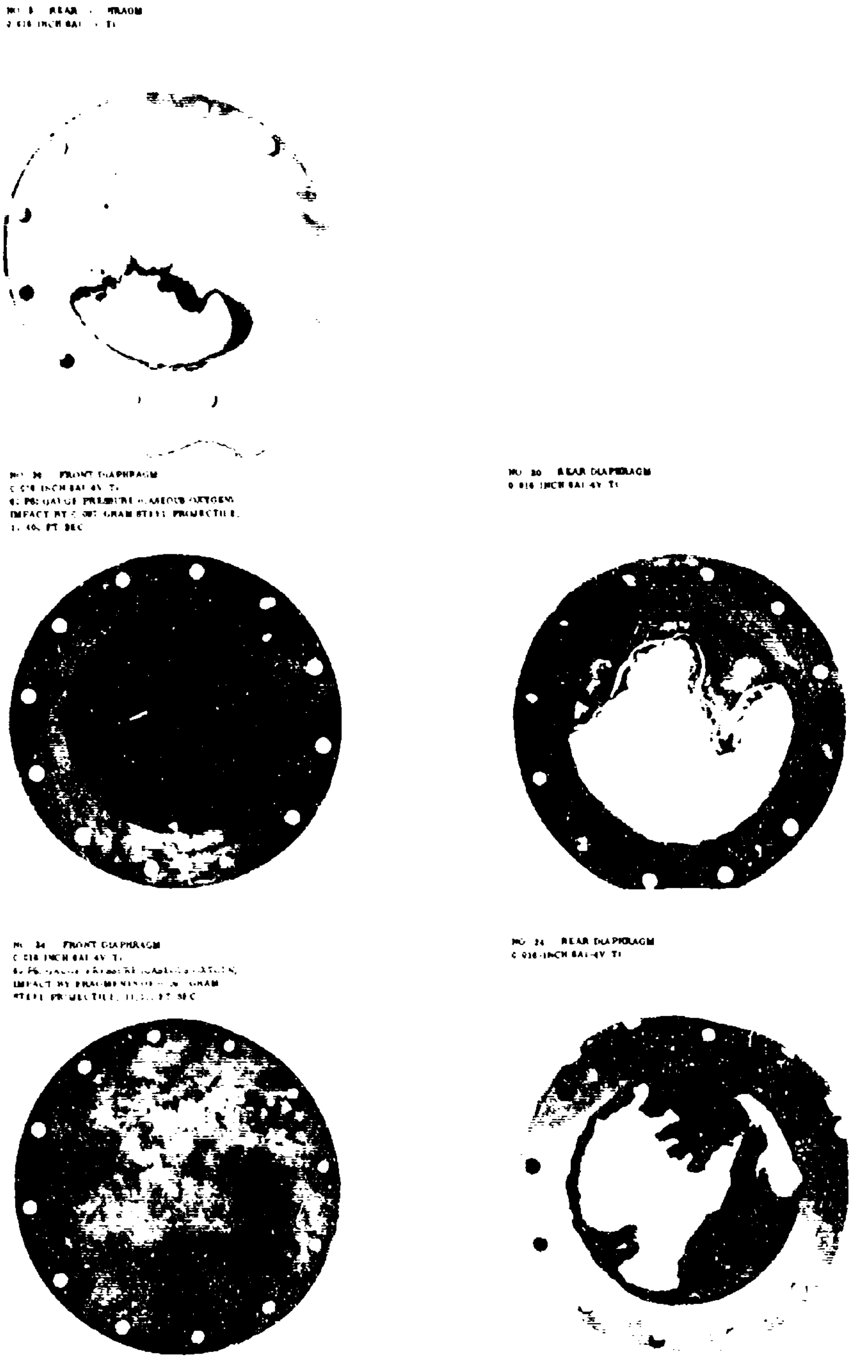


Figure 11. Test Panels 3, 10, 17, 20, and 24 (6Al-4



els 3, 10, 17, 20, and 24 (6Al–4V-Ti; 60-psi Gaseous Oxygen)

β

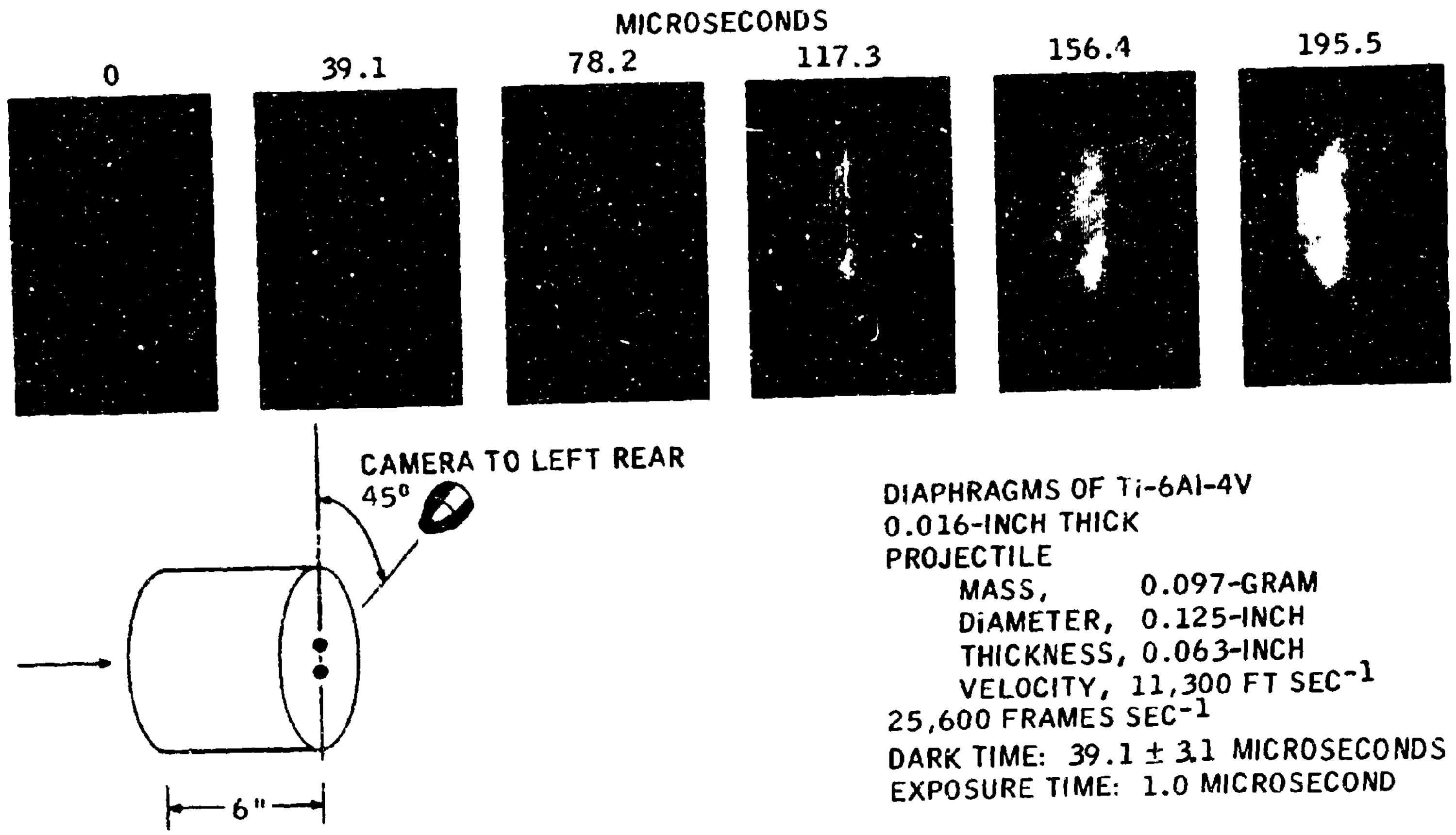
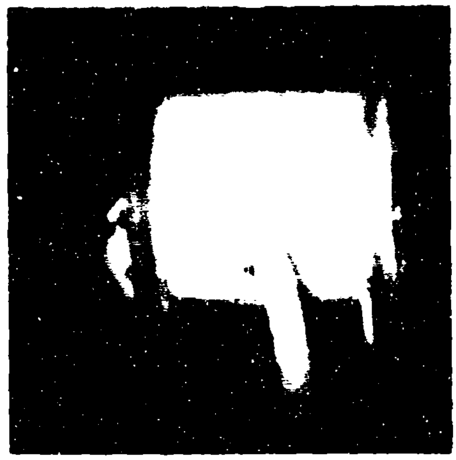
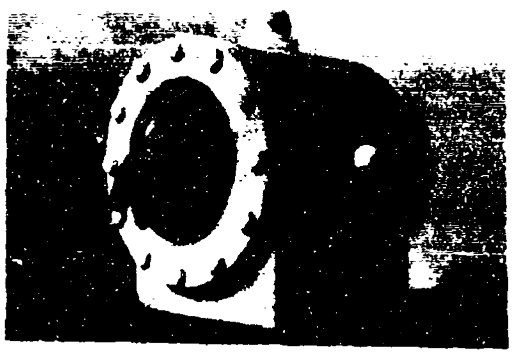


Figure 12. Test Panel 24 (Dynafax Photographs; 25,600 frames/sec)

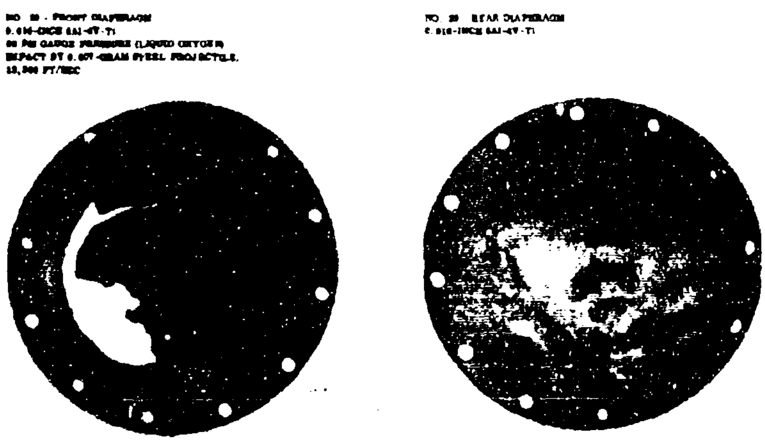
FRAME A. FRONT DIAPHRAGM RUPTURED.



FRAME B. 2.67 SECONDS AFTER IMPACT.

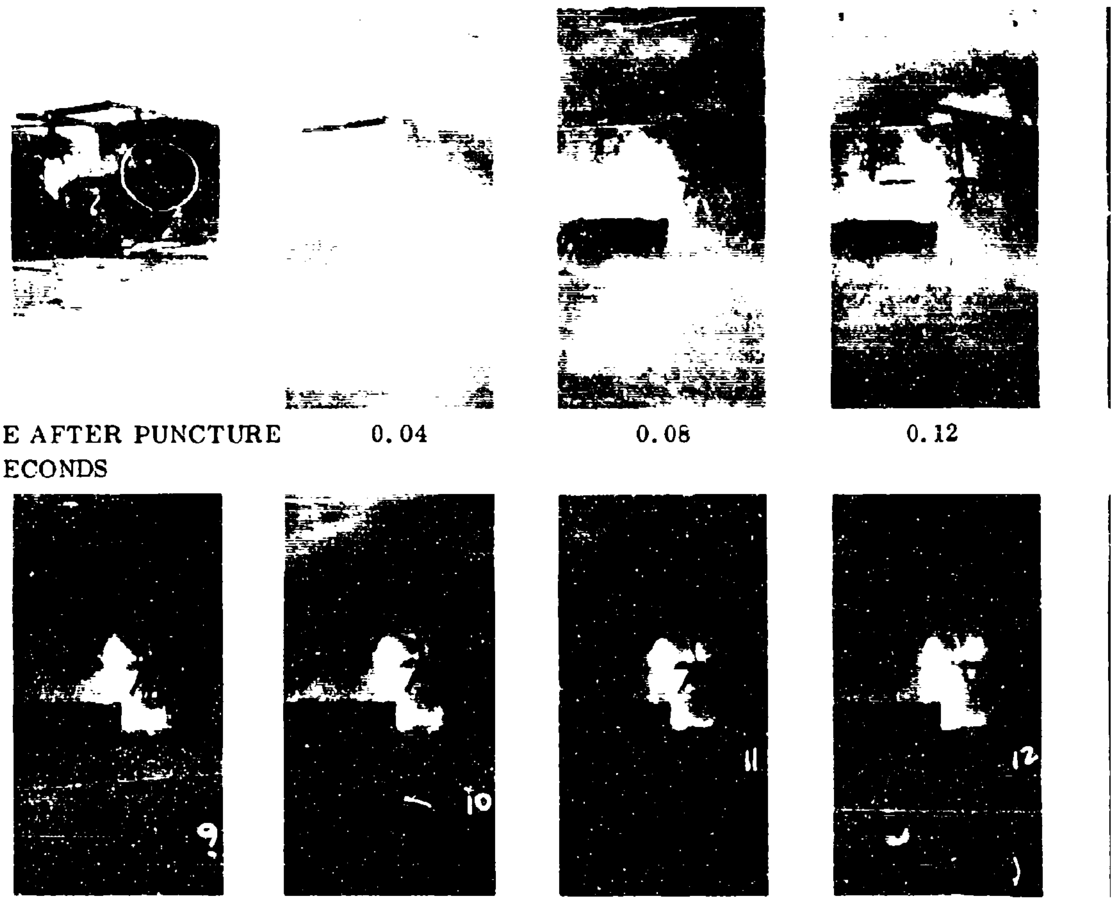


FRAME C.



FRAME D.

Figure 13. Test Panel 28 (6Al-4V-Ti; 0.097-Gram Projectile; 60-psi Gaseous Oxygen)

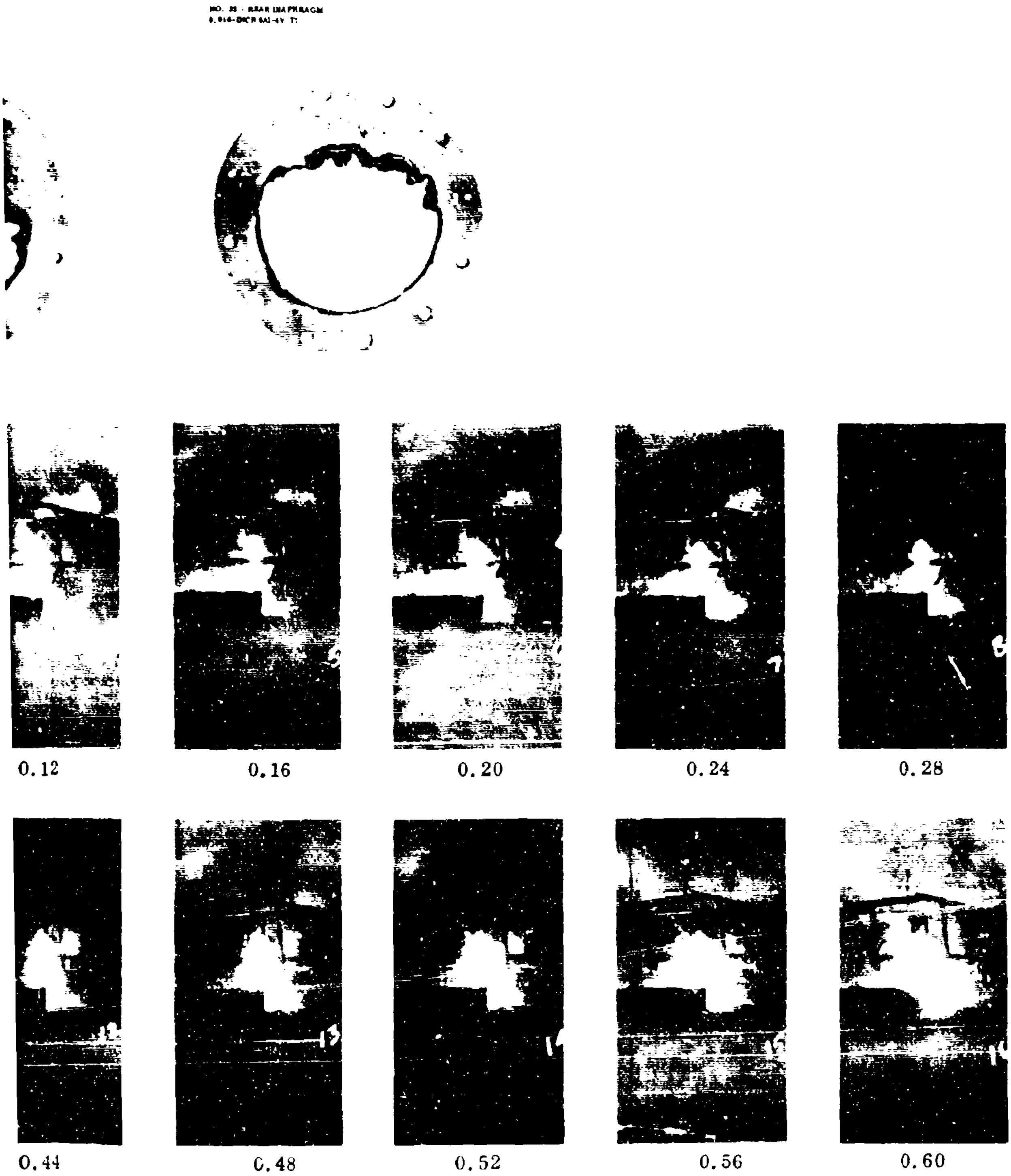


TIME AFTER PUNCTURE IN SECONDS

0.04 | 0.08 | 0.12

0.32 | 0.36 | 0.40 | 0.44

Figure 14. Test Panel 32 (6Al-4V-Ti; (



32 (6Al–4V–Ti; 0.097-Gram Projectile; 60-psi Liquid Oxygen)

3.2 ALUMINUM ALLOY (2024-T3). Seven experiments (Figures 15, 16, and 17) were made, using 0.016-inch aluminum (2024-T3) diaphragms pressurized to 60 psi; four (5, 11, 22, and 23) with gaseous oxygen, and three (31, 34, and 36) with liquid oxygen. The 0.097-gram projectile was used in all experiments, except numbers 5 (0.2066-gram) and 11 (0.1995-gram). The projectile broke up on acceleration to 6000 ft/sec in Experiment 5, and the numerous fragments produced 19 small holes in the front diaphragm, and 26 impacts with 10 small holes in the rear diaphragm. Both diaphragms were oxidized very slightly around the perforations. Projectile fragmentation also occurred in Experiment 11 (photograph not shown), and the particles at 6000 ft/sec produced six small holes in the front diaphragm without burning while the rear diaphragm was undamaged. The velocity was not determined in Experiment 22 (Figure 15), but it should be noted that the 0.097-gram projectile did not fragment on acceleration. It produced a single round hole (0.22-inch diameter) in the front diaphragm, and the fragments of projectile and shear plug perforated the rear diaphragm. These observations were verified in Experiment 23, although the projectile fragmented on acceleration.

Experiments 31, 34, and 36 were duplicates, using an impact velocity range of 11,600 to 12,300 ft/sec for the 0.097-gram projectile. Both diaphragms of the liquid-oxygen pressurized cylinder were penetrated, and slight oxidation occurred only at the rear diaphragm (Figure 16). Sequence photographs (Experiment 31 and Figure 17) show the jet of oxygen escaping from the punctures produced in the rear diaphragm of the pressurized aluminum (2024-T3) structure.

3.3 STAINLESS STEEL (FULL HARD 301). Seven experiments (9, 13, 19, 21, 27, 30, and 33) were made with both diaphragms of 0.010-inch thick, full extra-hard stainless steel, type 301, at a pressure of 60 psi. The projectile mass was 0.097 gram in all experiments, except No. 9, where the mass was 0.2154 gram.

Experiments 13, 19, and 21 were duplicates, using gaseous oxygen (Figure 18). The impact velocity of the 0.097-gram projectile in the velocity range from 11,600 to 13,500 ft/sec produced one hole (0.15 inch in Experiment 13 and 0.20 inch in Experiments 19 and 21), fragmented on impact with the front diaphragm, and the numerous fragments of projectile (4130 steel) and shear plug (301 stainless steel) perforated the rear diaphragm (in Experiment 13 a second very small hole was formed also). Neither excessive oxidation nor secondary explosions occurred. The conditions for Experiment 9 were identical to the previous three experiments (13, 19, and 21), except the projectile mass was greater; i.e., 0.2154 gram instead of 0.097 gram. This heavier projectile, with an impact velocity of 13,600 ft/sec, produced a single hole (0.25-inch diameter) in the front diaphragm (Figure 18) and perforated the rear diaphragm. An explosion occurred after the rear diaphragm was punctured, and several fragments struck and indented the back surface of the front diaphragm.

Three duplicate experiments (27, 30, and 33) were made, using liquid oxygen. However, the projectile in Experiment 30 (photograph not shown) struck the baffles,

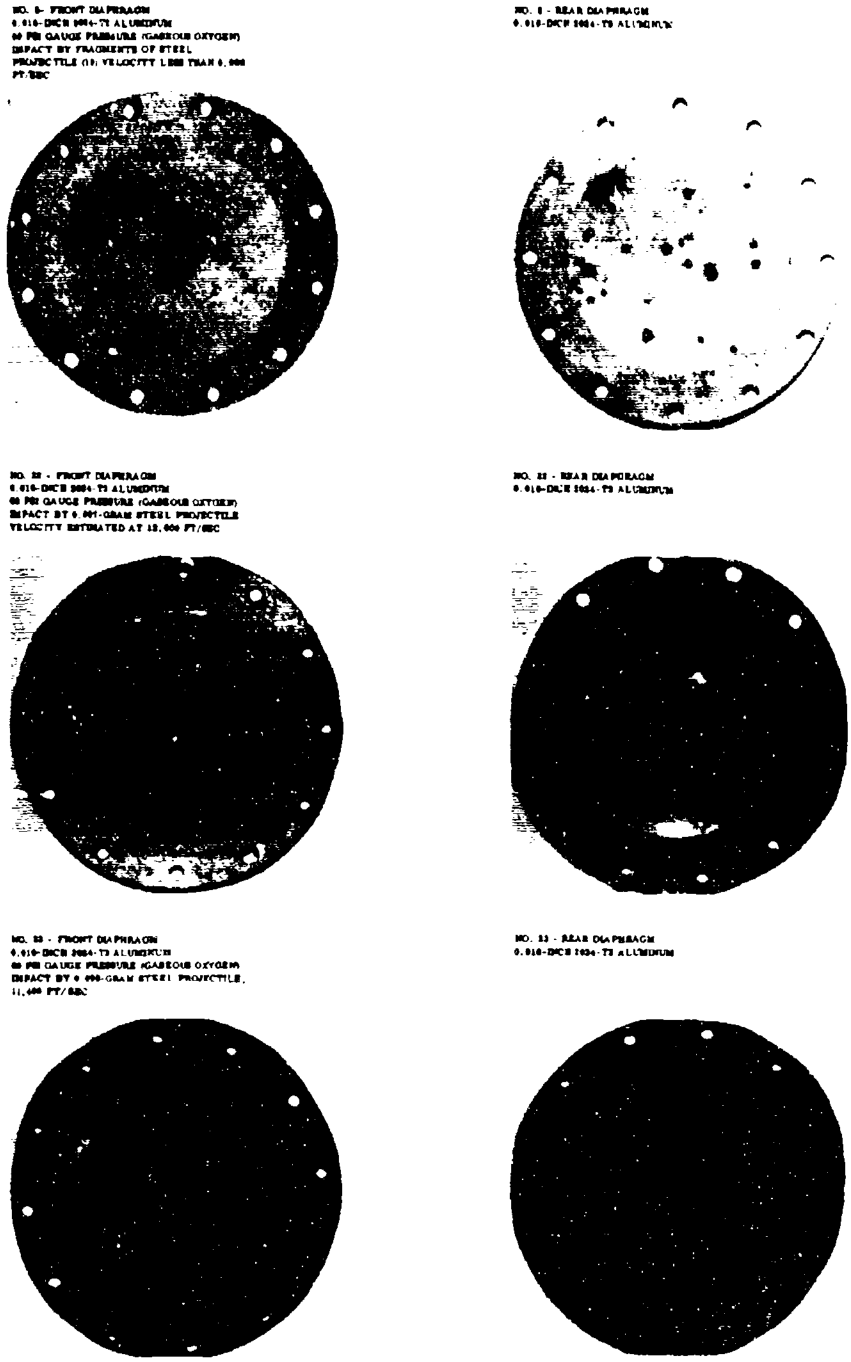


Figure 15. Test Panels 5, 22, and 23 (2024-T3 Aluminum; 0.097-Gram Projectile; 60-psi Gaseous Oxygen)

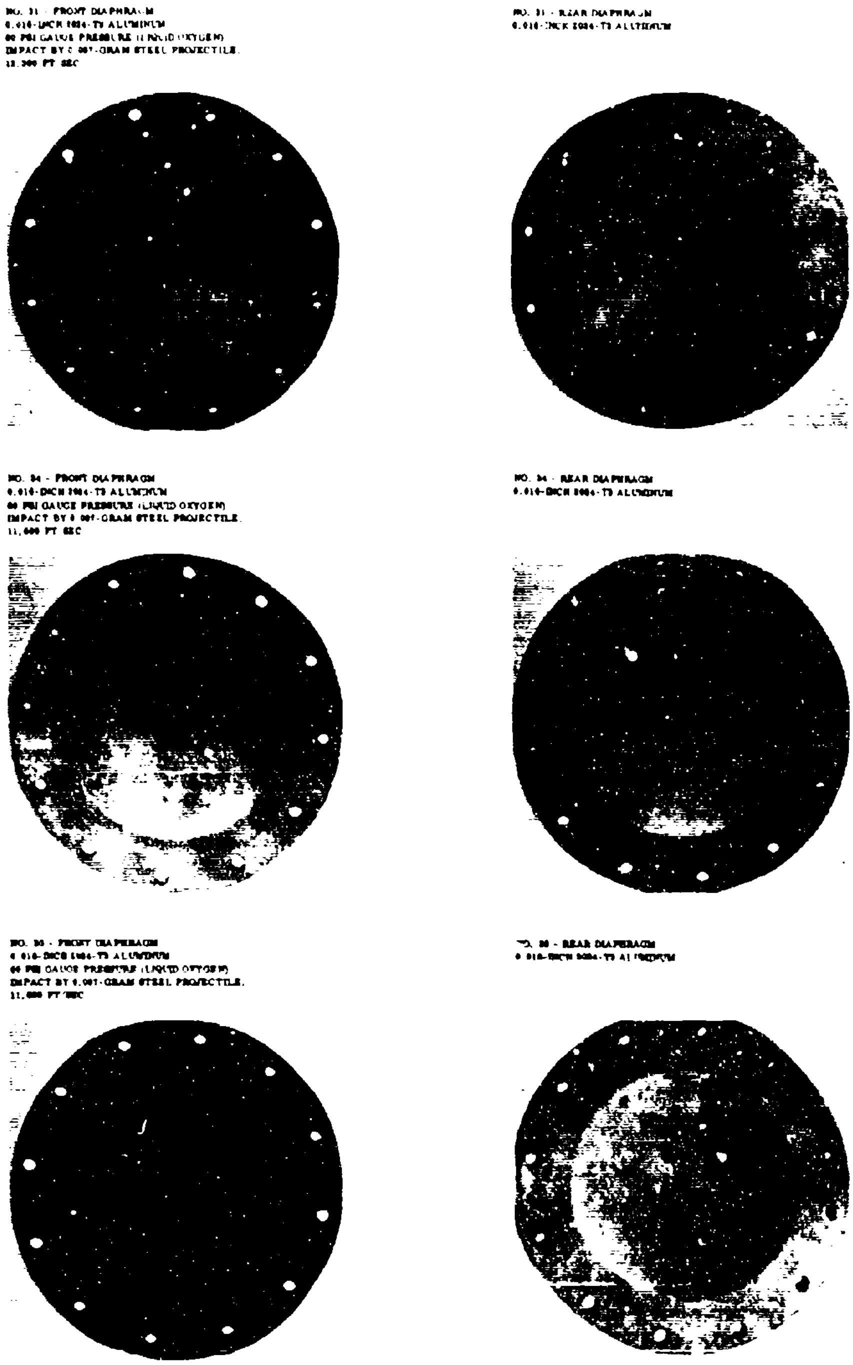


Figure 16. Test Panels 31, 34, and 36 (2024-T? Aluminum; 0.097-Gram Projectile; 60-psi Liquid Oxygen)

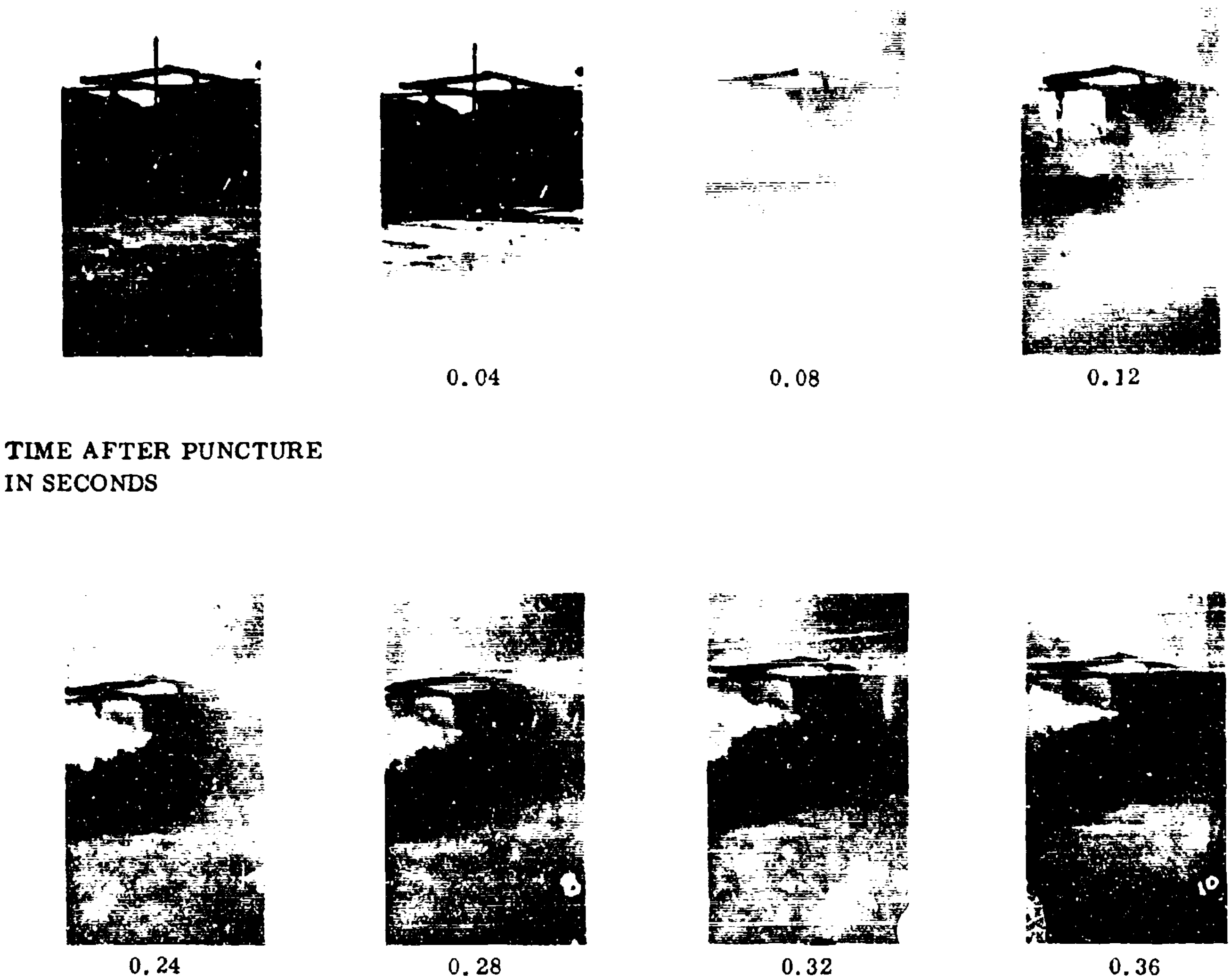
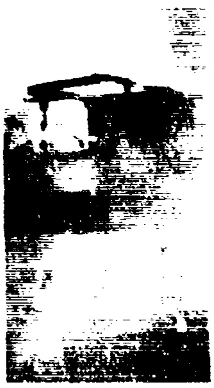
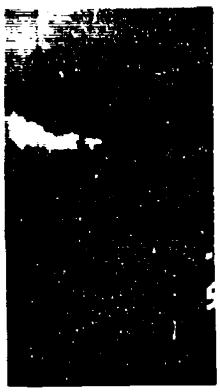


Figure 17. Test Panel 31 (2024-T3 Aluminum; 0.097-Gram Projec



0.12



0.16

0.20

0.36

0.40

0.44

Aluminum; 0.097-Gram Projectile; 60-psi Liquid Oxygen)

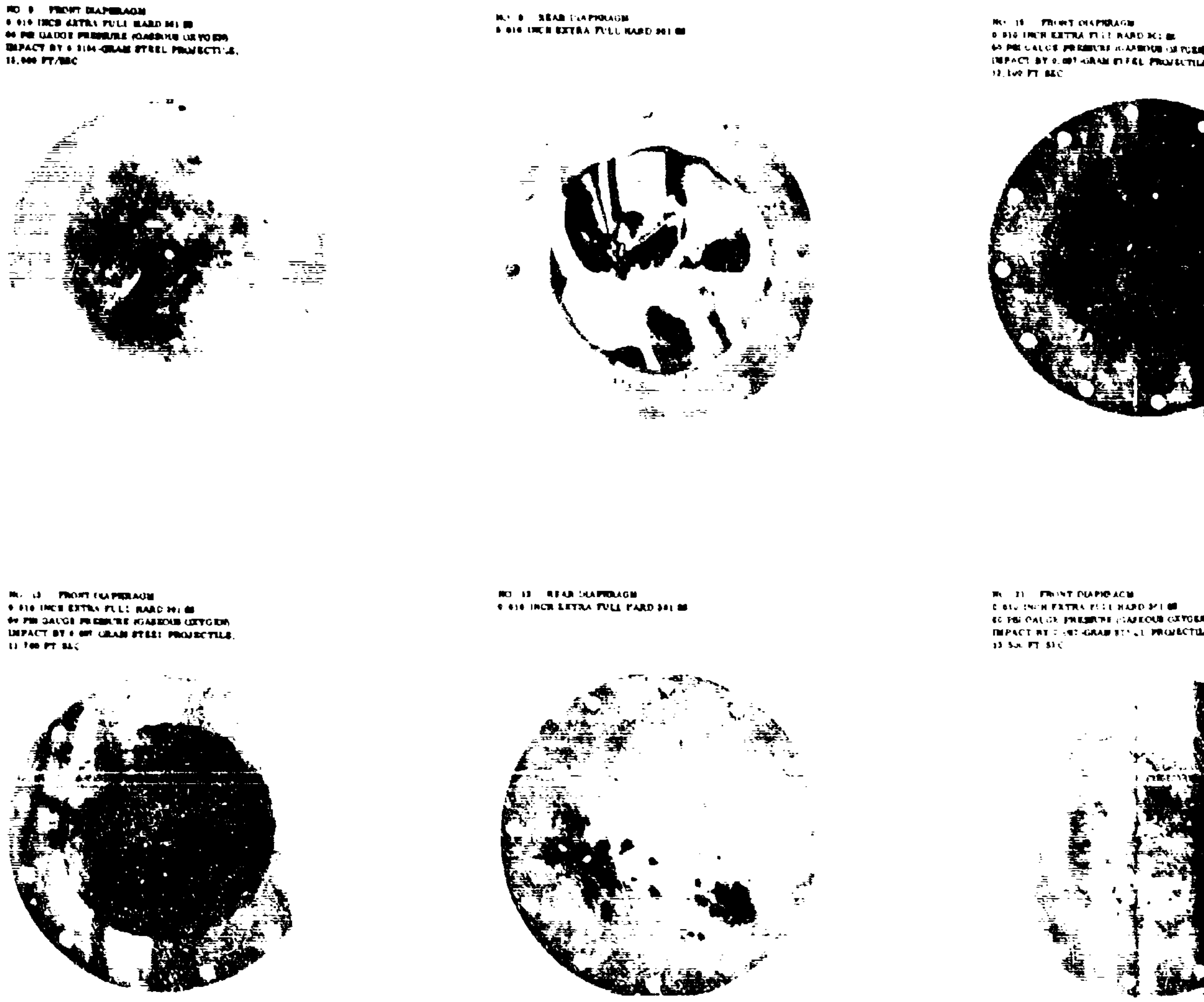
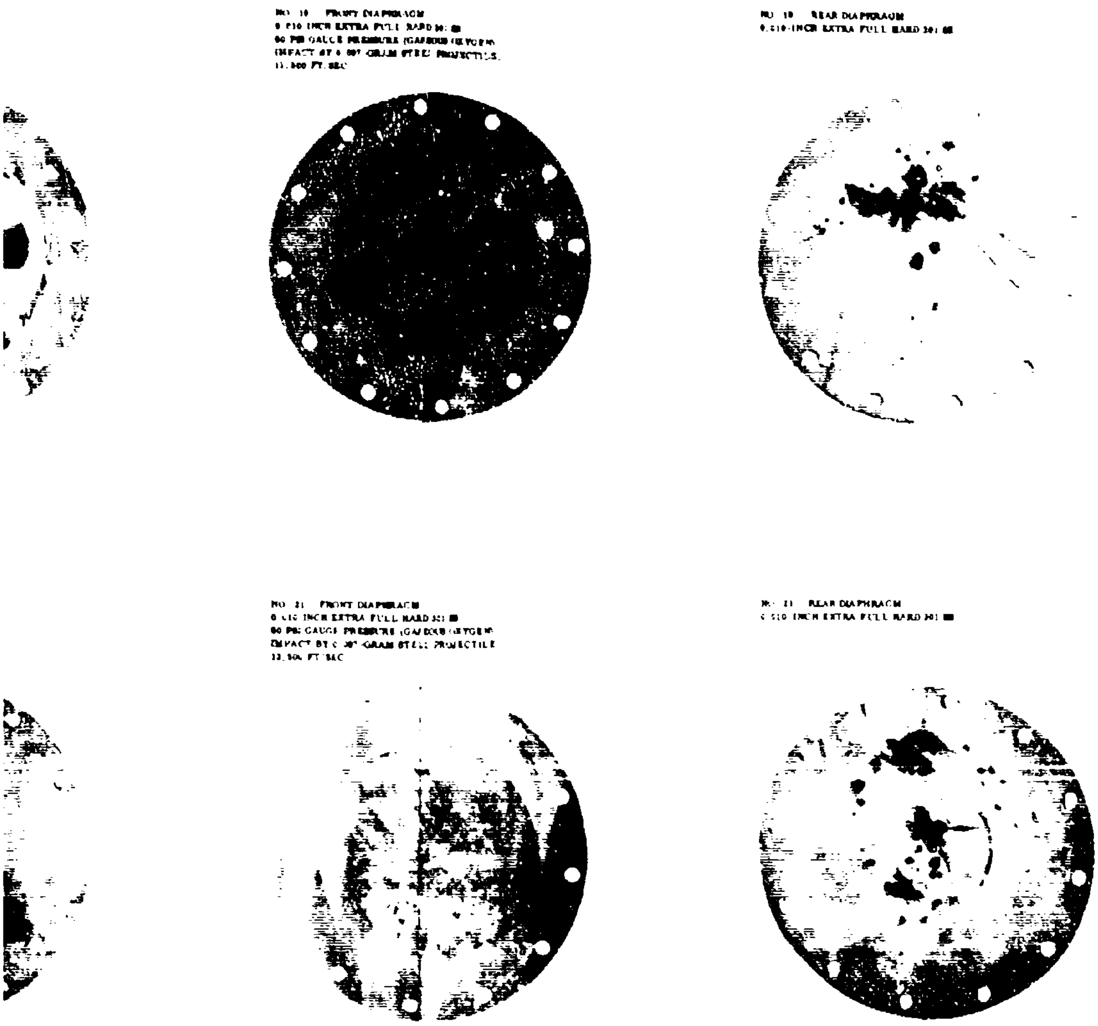


Figure 18. Test Panels 9, 13, 19, and 21 (Stainless St



B

Panels 9, 13, 19, and 21 (Stainless Steel 301; 60-psi Gaseous Oxygen)

fragmented, and only one small particle penetrated the front diaphragm with no damage to the rear diaphragm. The projectile impact velocity of 11/600 ft/sec in Experiments 27 and 33 (Figure 19) produced the following: a single hole (0.15-inch diameter) in the front diaphragm in Experiment 27, and a single hole (0.1 by 0.18 inch) in the front diaphragm in Experiment 33; both rear diaphragms were penetrated and perforated with no other damage.

3.4 FRONT AND REAR DIAPHRAGMS OF DIFFERENT MATERIALS. Front and rear diaphragms used in Experiment 6 were 0.025-inch 5Al-2.5Sn-Ti and 0.016-inch 2024-T3 aluminum, respectively. The 0.2085-gram projectile, with an impact velocity of 12,500 ft/sec, struck the front titanium diaphragm. The fragments of steel and titanium alloy produced 35 craters and 16 small holes in the rear aluminum diaphragm. As a result of this impact on the cylinder, pressurized to 60 psi with gaseous oxygen, the front diaphragm of titanium burned (approximately 25 percent) while the rear diaphragm of aluminum did not react (Figure 20).

Front and rear diaphragms in Experiment 8 were 0.016-inch 2024-T3 aluminum and 0.025-inch 5Al-2.5Sn-Ti, respectively. The impact velocity was not measured on the cylinder pressurized to 60 psi with gaseous oxygen. In this experiment, the front diaphragm of aluminum was penetrated (19 small holes) while the rear diaphragm of titanium burned (45 percent).

3.5 SANDWICH PANELS

3.5.1 Aluminum-Titanium. Front and rear diaphragms of test panel 40 were identical and fabricated from a 0.016-inch sheet of 6Al-4V-Ti placed between 0.016-inch sheets of 2024-T3 aluminum. Each pair of three sheets, which comprised one diaphragm, were pressed together between the flanges of the test cylinder, pressurized to 60 psi with liquid oxygen, and subjected to impact from the 0.097-gram projectile traveling at 9300 ft/sec. The six sheets of metal in the two diaphragms were penetrated and burned as seen in Figure 21. The presence of titanium is detrimental to aluminum, since the aluminum panels were almost totally burned under the experimental conditions.

3.5.2 Stainless Steel-Titanium. Front and rear diaphragms of test panel 41 were identical and fabricated from a 0.016-inch sheet of 6Al-4V-Ti placed between 0.010-inch sheets of full hard 301 stainless steel. Each pair of three sheets, which comprised one diaphragm, were pressed together between the flanges of the test cylinder pressurized to 60 psi with liquid oxygen and subjected to impact from the 0.097-gram projectile traveling at 9100 ft/sec. The projectile penetrated the three sheets of the front diaphragm, but the fragments did not penetrate any of the sheets in the rear diaphragm. However, the impact shock almost ruptured the entire rear diaphragm at the contact between the diaphragm and the cylinder flange. Three small discolored spots were formed on the stainless steel (rear of the No. 1 sheet) in contact with the liquid oxygen. It can be seen in Figure 22 that the three panels in the front diaphragm were not only

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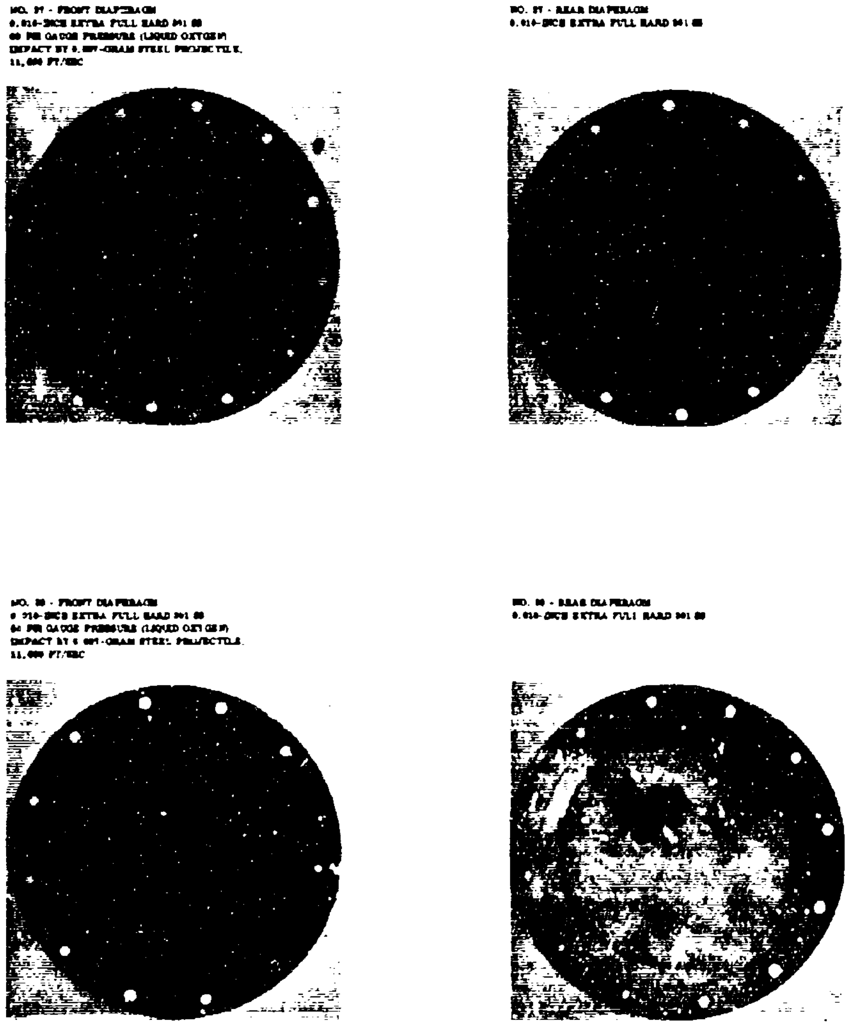


Figure 19. Test Panels 27 and 33 (Stainless Steel 301; 0.097-Gram Projectile; 60-psi Liquid Oxygen)

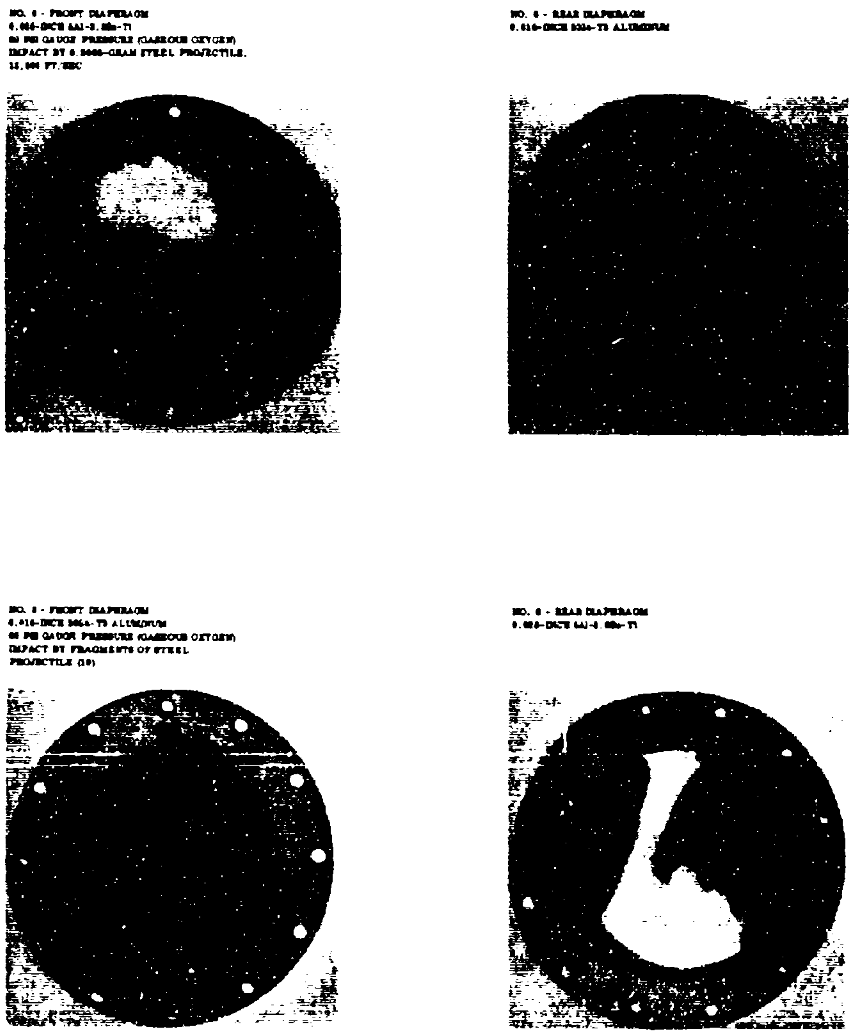


Figure 20. Test Panels 6 and 8 (Diaphragms of Different Material)

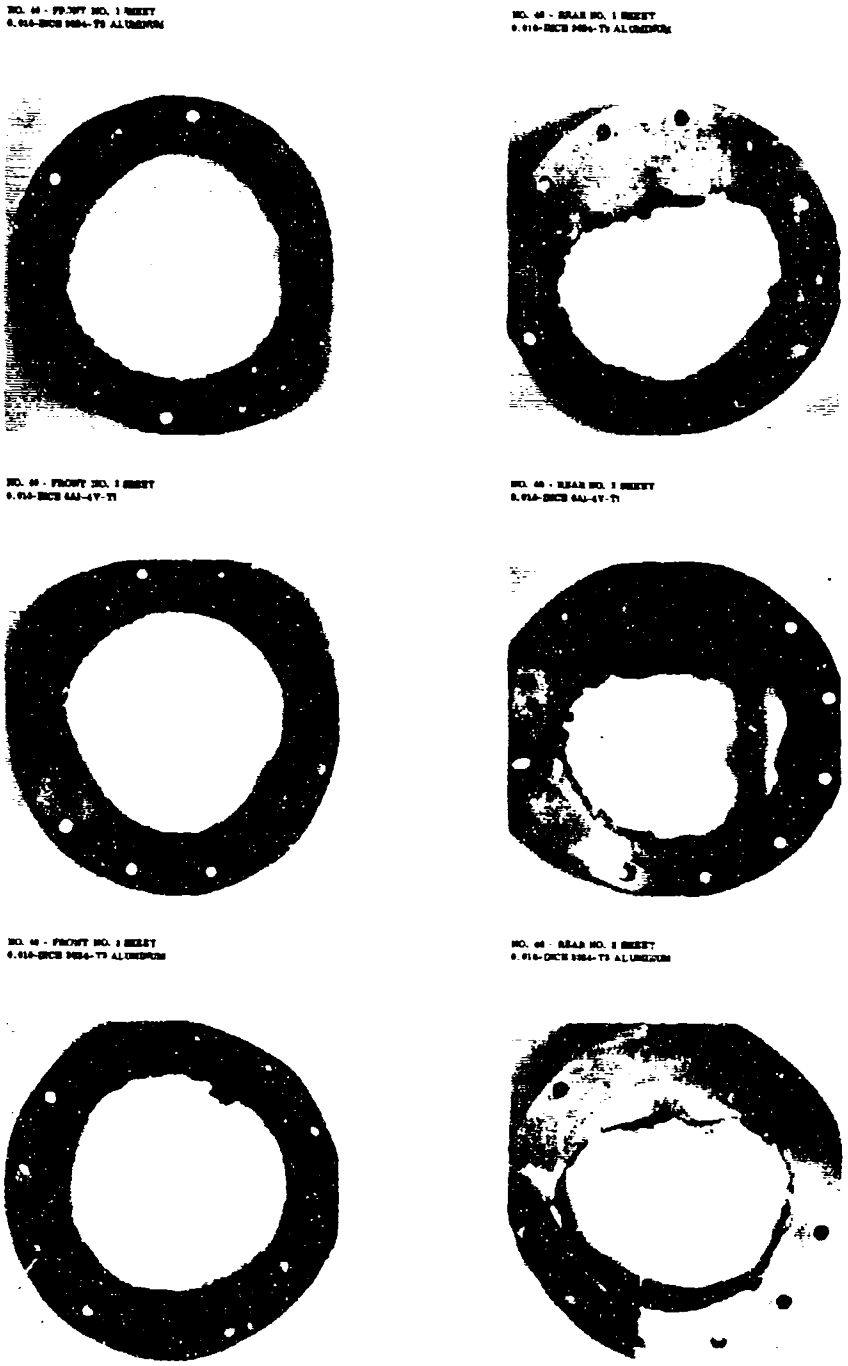


Figure 21. Test Panel 40 (Aluminum-Titanium Sandwich; 60-psi Liquid Oxygen; Impact by 0.097-Gram Steel Projectile, 9,300 ft/sec)

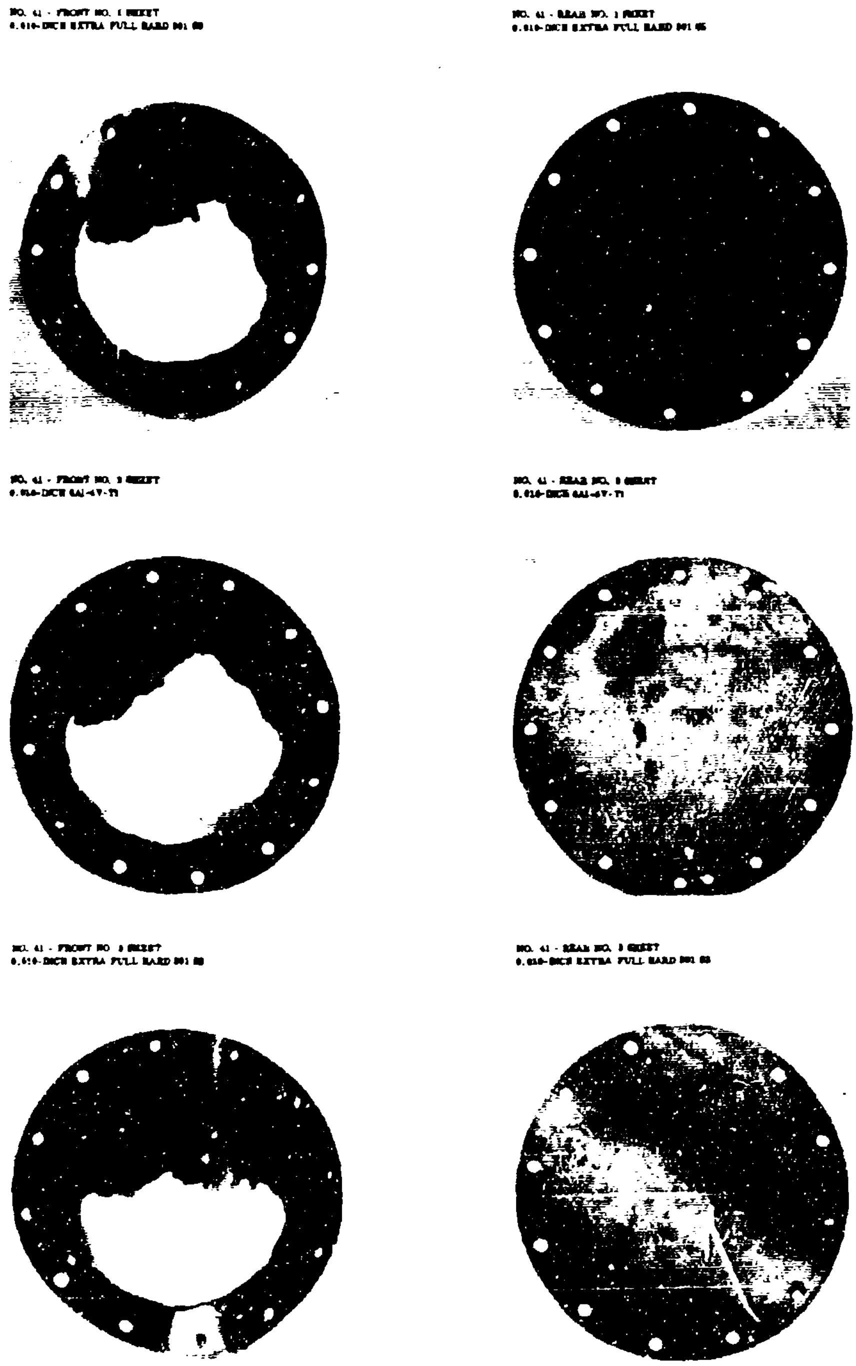


Figure 22. Test Panel 41 (Stainless Steel-Titanium Sandwich; 50-psi Liquid Oxygen; Impact by 0.097-Gram Steel Projectile, 9,300 ft/sec)

penetrated but were extensively burned. The presence of titanium is detrimental to stainless steel since the steel panels were extensively burned under the experimental conditions.

3.6 RETARDANT WD-40* on 6Al-4V-Ti

3.6.1 Both Surfaces of a Diaphragm Coated. A 0.016-inch sheet of titanium alloy (6Al-4V-Ti), coated with a triple layer of WD-40 on both surfaces, comprised both diaphragms used in Experiments 43, 44, 49, and 51. Both diaphragms in Experiments 43 and 44, pressurized to 60 psi with liquid oxygen, and struck with the 0.097-gram projectile traveling at 13,000 ft/sec were penetrated. The front diaphragm burned in Experiment 43, while only the rear diaphragm burned in Experiment 44 (Figure 23). However, neither titanium alloy diaphragms of the gaseous oxygen pressurized cylinder (Experiment 51) burned, although both were penetrated with the 0.097-gram projectile traveling at 12,500 ft/sec. The fragments of projectile and titanium alloy removed from the front diaphragm perforated the rear diaphragm (Figure 23).

3.6.2 Exterior Surface of Both Diaphragms Coated. A 0.016-inch sheet of titanium alloy (6Al-4V-Ti), coated with a triple layer of WD-40 on the exterior surface, comprised both diaphragms used in Experiments 45, 47, 48, and 50.

The front diaphragms of Experiments 45 and 47, pressurized to 60 psi with liquid oxygen, and struck with the 0.097-gram projectile traveling at 12,200 ft/sec, were penetrated and burned. It can be seen in Figure 24 that the rear diaphragm of Experiment 47 was also severely burned while that of Experiment 45 was undamaged. This lack of damage to the rear diaphragm (Experiment 45) can be attributed to the explosion which ruptured the front diaphragm and released the pressure on the cylinder. A secondary explosion (see footnote on page 21) or rupture occurred, and this can be deduced from the unburned fracture surface that still remains on the test panel (Figure 24).

The front diaphragms of Experiments 48 and 50, pressurized to 60 psi with gaseous oxygen and struck with the 0.097-gram projectile traveling at 11,600 ft/sec, were penetrated without burning while the rear diaphragms were burned (Figure 24).

*WD-40 is a proprietary material of the Rocket Chemical Company, San Diego, California. This material dries to a thin, tacky film that has excellent corrosion resisting qualities, and has been found to reduce the incidence of ignition of titanium under test conditions.

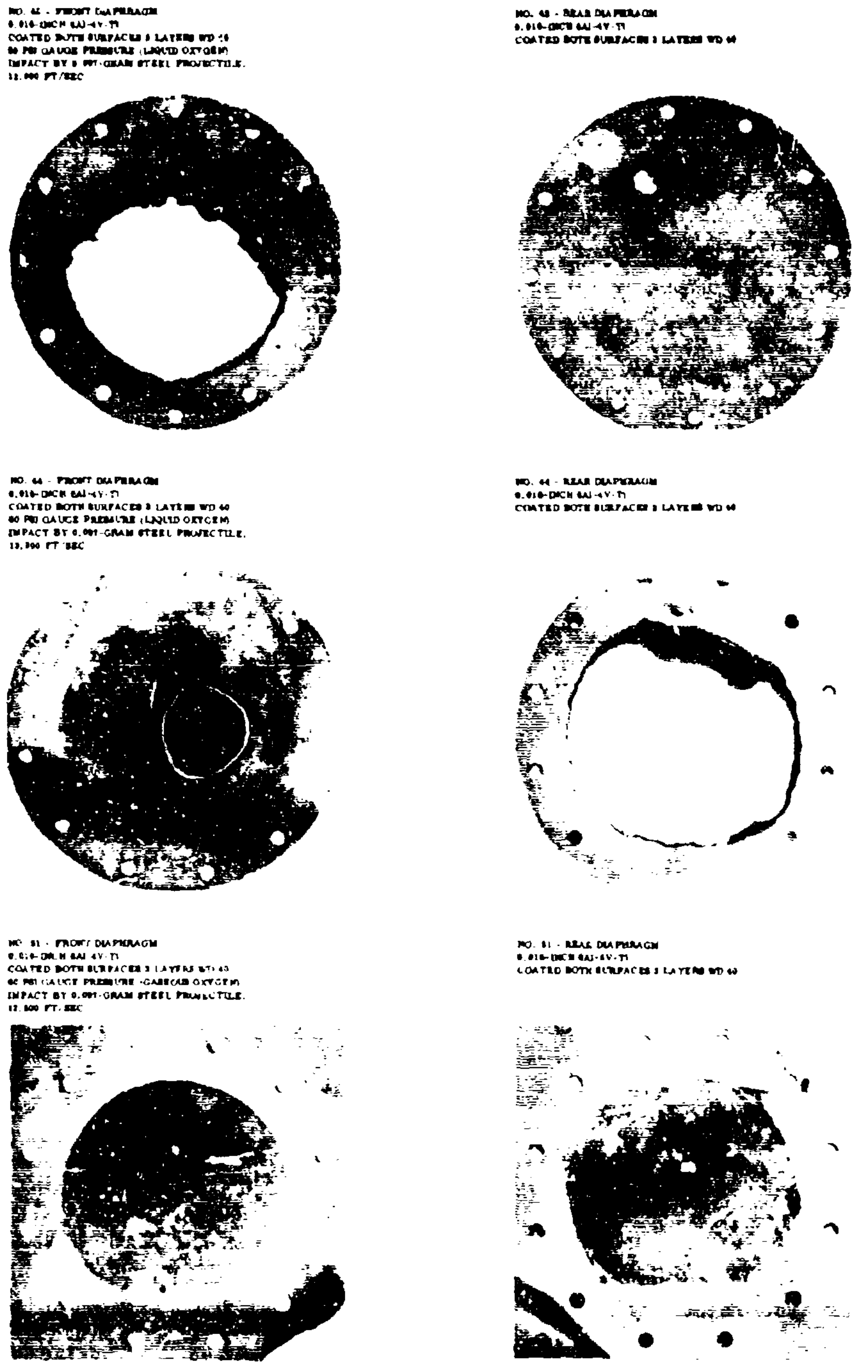
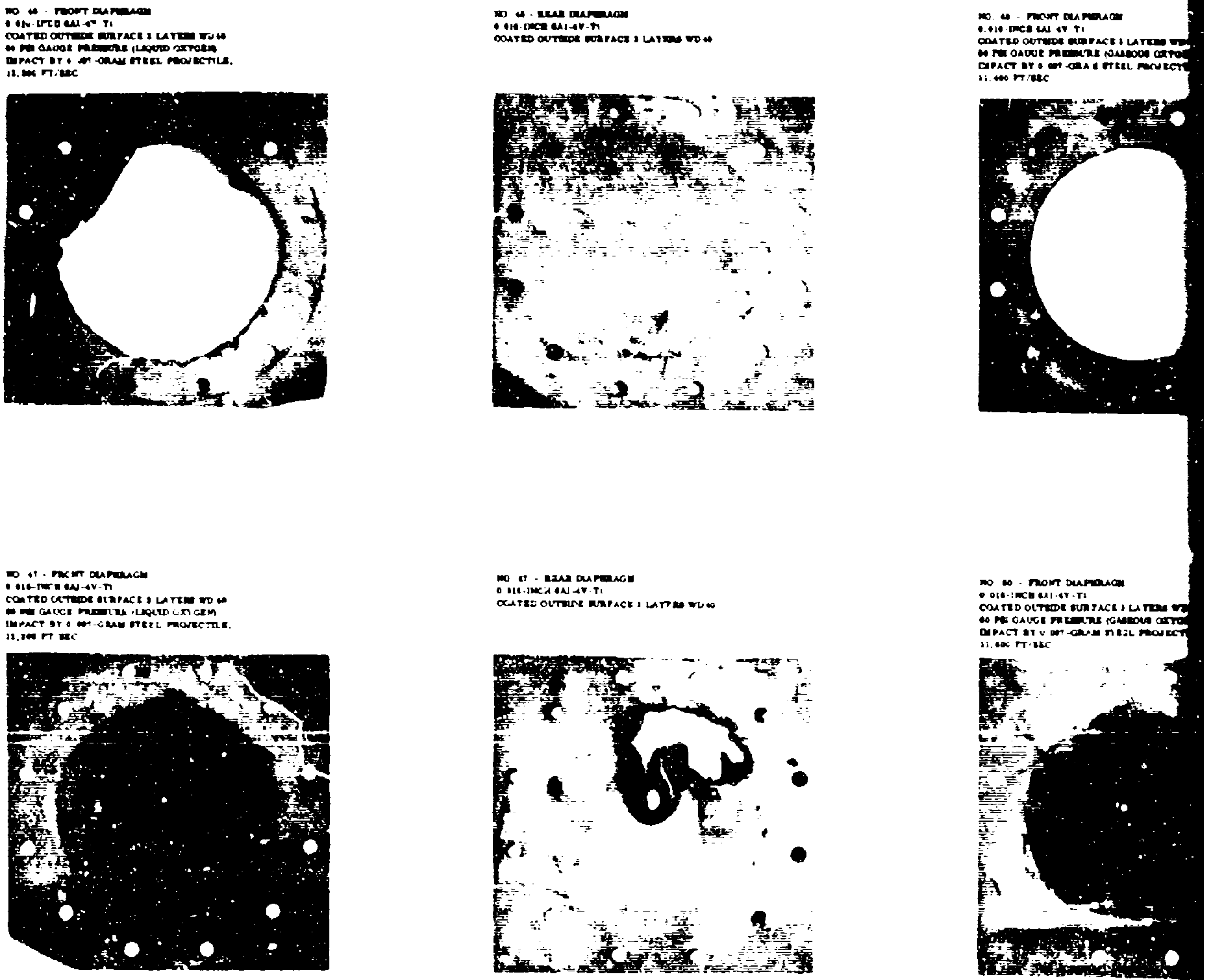


Figure 23. Test Panels 43, 44, and 51 (Both Surfaces of 6Al-4V-Ti Coated with WD-40)



A

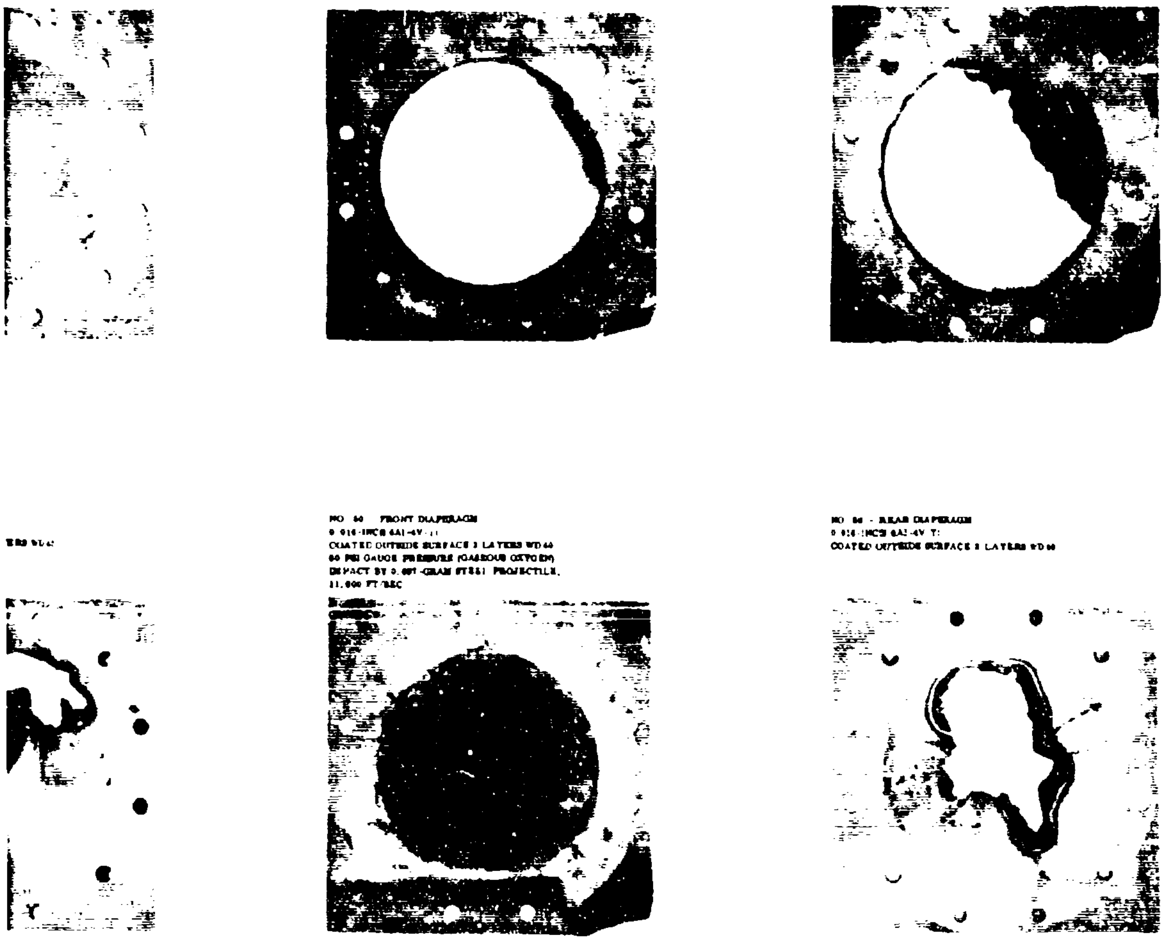
Figure 24. Test Panels 45, 47, 48, and 50 (Exterior Surfa

NO. [illegible] - FRONT DIAPHRAGM
0.016-INCH 6Al-4V-Ti
COATED OUTSIDE SURFACE 1 LAYERS WD40
60 PSI GAUGE PRESSURE (GASEOUS OXYGEN)
IMPACT BY 0.[illegible]-GRAM STEEL PROJECTILE,
11,[illegible] FT/SEC

NO. [illegible] - REAR DIAPHRAGM
0.016-INCH 6Al-4V Ti
COATED OUTSIDE SURFACE 1 LAYERS WD40

NO. [illegible] - FRONT DIAPHRAGM
0.016-INCH 6Al-4V-Ti
COATED OUTSIDE SURFACE 3 LAYERS WD40
60 PSI GAUGE PRESSURE (GASEOUS OXYGEN)
IMPACT BY 0.[illegible]-GRAM STEEL PROJECTILE,
11,000 FT/SEC

NO. [illegible] - REAR DIAPHRAGM
0.016-INCH 6Al-4V Ti
COATED OUTSIDE SURFACE 3 LAYERS WD40



B

Panels 45, 47, 48, and 50 (Exterior Surfaces of 6Al-4V-Ti-Coated with WD-40)

4 SUMMARY AND DISCUSSION

4.1 SUMMARY. It can be concluded from the data presented phenomenologically in the previous sections that:

a. Pressurized structures will not rupture or lose pressure when subjected to the shock wave generated with a one pound explosive charge at a distance of 4-1/2 feet.

b. The projectile, heated from both the explosive and the flight through the air, will not cause all pressurized structures to either burn or explode.

c. Aluminum alloy 2024-T3 does not chemically react catastrophically with gaseous or liquid oxygen when diaphragms pressurized to 60 psi are struck with steel projectiles weighing 0.097 to 0.2066 gram traveling at a velocity up to 12,300 ft/sec. The 0.016-inch front diaphragms will successfully fragment the steel projectile (see Experiments 5, 6, 8, 22, 23, 31, 34, and 36; Figures 15, 16, and 20).

d. Full hard stainless steel 301 does not chemically react catastrophically with gaseous or liquid oxygen when diaphragms pressurized to 60 psi are struck with steel projectiles weighing 0.097 to 0.2154 gram traveling in the velocity range from 8,900 to 13,600 ft/sec. The 0.010-inch front diaphragm successfully fragmented the steel projectile (see Experiments 9, 13, 19, 21, 27, 30, and 33; Figures 18 and 19).

e. Titanium alloy (5Al-2.5Sn-Ti) chemically reacts catastrophically with gaseous or liquid oxygen when diaphragms pressurized (20 to 60 psi) are struck with steel projectiles weighing 0.097 to 0.2190 gram traveling in the velocity range of 9100 to 15,900 ft/sec. The front diaphragm of gaseous oxygen pressurized cylinders was penetrated, while the rear diaphragm chemically reacted and burned. Either one or both diaphragms of liquid-oxygen pressurized cylinders react chemically (see Experiments 1, 2, 4, 6, 8, 18, 29, 35, 37, 38, 39; Figures 5, 6, 7, and 20).

f. Titanium alloy (6Al-4V-Ti) chemically reacts catastrophically with gaseous or liquid oxygen when diaphragms, pressurized to 60 psi, are struck with steel projectiles weighing 0.097 to 0.2127 gram traveling in a velocity range from 10,900 to 15,100 ft/sec. Either or both diaphragms can chemically react (see Experiments 3, 10, 17, 20, 24, 28, and 32; Figures 11, 13 and 14).

g. Coatings of WD-40 retard the chemical reactivity of titanium alloy (6Al-4V-Ti) diaphragms pressurized to 60 psi with gaseous oxygen and struck with steel projectiles weighing 0.097 gram traveling in the velocity range from 11,400 to 12,500 ft/sec (see Experiments 48, 50, and 51; Figures 23 and 24).

4 SUMMARY AND DISCUSSION

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d. Full hard stainless steel 301 does not chemically react catastrophically with gaseous or liquid oxygen when diaphragms pressurized to 60 psi are struck with steel projectiles weighing 0.097 to 0.2154 gram traveling in the velocity range from 8,900 to 13,600 ft/sec. The 0.010-inch front diaphragm successfully fragmented the steel projectile (see Experiments 9, 13, 19, 21, 27, 30, and 33; Figures 18 and 19).

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g. Coatings of WD-40 retard the chemical reactivity of titanium alloy (6Al-4V-Ti) diaphragms pressurized to 60 psi with gaseous oxygen and struck with steel projectiles weighing 0.097 gram traveling in the velocity range from 11,400 to 12,500 ft/sec (see Experiments 48, 50, and 51; Figures 23 and 24).

h. Coatings of WD-40 do not appear to retard the chemical reactivity of titanium alloy (6Al-4V-Ti) diaphragms pressurized to 60 psi with liquid oxygen struck with steel projectiles weighing 0.097 gram and traveling in the velocity range of 12,200 to 13,200 ft/sec (see Experiments 43, 44, 45, and 47; Figures 23 and 24).

i. Full hard stainless steel 301 or aluminum 2024-T3 structures subjected to an impulsive load cannot be used when in contact with titanium alloys (6Al-4V-Ti or 5Al-2.5Sn-Ti) in a pure liquid or gaseous oxygen environment (see Experiments 40 and 41; Figures 21 and 22).

j. At least three pressurized cylinders exploded from either the projectile impact or the shock wave generated from the impact. Two cylinders that exploded were fabricated with titanium alloy diaphragms, while the third was made from stainless steel (see Experiments 9, 28, and 45; Figures 13, 18, and 24).

k. Titanium (6Al-4V-Ti) will not burn in air (sea level environment) when struck with the 0.097-gram projectile traveling at 10,900 ft/sec (see Experiment 42 and Figure 25).

l. Titanium (6Al-4V-Ti) will not burn in a pure gaseous nitrogen environment when struck with the 0.097-gram projectile traveling at 12,200 ft/sec (see Experiment 26 and Figure 26).

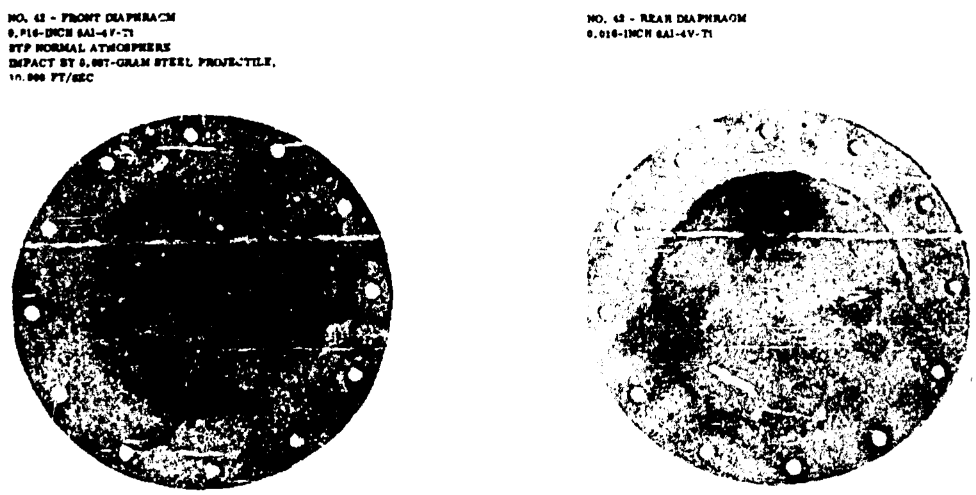


Figure 25. Test Panel 42 (6Al-4V-Ti; 0.097-Gram Projectile; Sea-Level Environment)

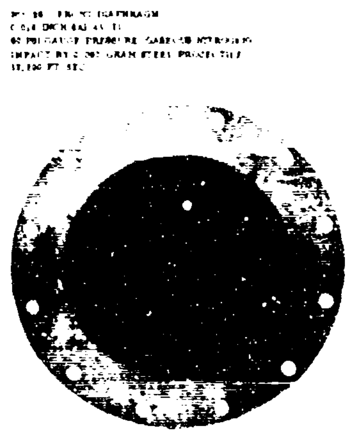


Figure 26. Test Panel 26 (6Al 4V-Ti; 0.097-Gram Projectile; 60-psi Gaseous Nitrogen)

m. One test cylinder, with both diaphragms fabricated from titanium (6Al-4V-Ti), and each diaphragm coated on both sides with WD-40, did not burn or explode when struck with the 0.097-gram steel projectile traveling at 12,500 ft/sec. This experimental result should be verified (see Experiment 51 and Figure 23).

4.2 DISCUSSION. The use of titanium at elevated temperatures is restricted by its reactivity with oxygen. Titanium reacts exothermically with oxygen [$Ti + O_2 \longrightarrow TiO_2$ (rutile)] at 610°C and the heats and free energy of formation are -225.5 and -212.4 kcal/mole, respectively (it should be recognized that the thermodynamic values are those for the pure elements and not the alloys under consideration). Aluminum reacts exothermically with oxygen (Al_2O_3, corundum) and the heat and free energy of formation are -396.19 and -399.09 kcal/mole, respectively. Aluminum reacts with nitrogen at 150°C and the reaction becomes exothermic at 820°C. The iron nitrides are unstable as evidenced from the positive values for the free energy of formation; i.e., the free energy values are +2.6 and 0.89 kcal/mole for Fe_2N and Fe_4N, respectively. Additional physical data are summarized in Table 4.

Stainless steel, aluminum, and titanium have excellent corrosion resistance and this inactivity can be attributed largely to the formation of a passive oxide surface film. It is because of this film that titanium is resistant to attack in most oxidizing media. This oxide film is protective only up to moderate temperatures since oxidation of titanium occurs very slowly at temperatures as low as 480°F (249°C) and the

Table 4. Physical Properties[1] of Several Metals

MATERIAL	HEAT CAPACITY (ROOM TEMPERATURE) cal/°C/mole	HEAT CAPACITY (ROOM TEMPERATURE) cal/°C/cm^3	THERMAL CONDUCTIVITY (ROOM TEMPERATURE) hr/ft^2/(°F ft)	APPROXIMATE IGNITION POINT IN OXYGEN (°C)
Al	5.8	0.58	117	over 1000
Cu	10.8	1.51	220	---
Cr	5.7	0.78	---	2000
Fe	6.1	0.84	26	930
Mg	5.9	0.42	92	540-625
Ni	6.2	0.93	35	---
Stainless Steel	6.6	0.96	9	---
Ti	4.4	0.42	14	610
Zr	---	----	---	1400

oxidation rate increases as the temperature is increased. The oxidation of titanium follows the parabolic rate law with time at any given temperature. In addition to the oxidation reaction, there is also a diffusion of oxygen into titanium which enters into solid solution and hardens and embrittles the metal. The diffusion of oxygen into titanium is also temperature dependent so that both oxidation and diffusion take place.

Corrosion of metal surfaces is not a problem in liquid oxygen. There can be no doubt, however, that some metals may be reactive to liquid oxygen under conditions of high impact. It has been reported (Reference 2) that high surface area metal, as exhibited by metal wool of aluminum, steel, stainless steel, and magnesium, will react under liquid oxygen when impacted with 72 ft-lb of energy by a dropped weight (the titanium reaction has been observed to occur at impact energies as low as 10 ft-lb, however, at a considerably lower incidence of reaction). Titanium is especially reactive in the massive state and titanium alloys are slightly more reactive.

Metals will ignite when the energy of an oxidation reaction overcomes the conductive, convective, and radiative cooling. Ignition is brought about by an exothermic reaction that takes place between the metal and the gaseous oxygen environment. Critical pressure limits required to produce a spontaneous reaction (negative free energy of formation) depends on the oxygen concentration.

Under static conditions at room temperature, titanium will spontaneously ignite when it is in pure (100 percent) oxygen at pressure of 350 psi or greater, whereas, only 45 percent by volume of oxygen is required at a pressure of 2000 psi. These values apparently depend on the availability of a fresh titanium surface to permit the reaction to initiate. Less severe conditions are needed under dynamic conditions. For example, titanium will ignite in pure flowing oxygen when the total pressure is as low as 50 psi. The limiting oxygen concentration is about 35 percent. Once the reaction is initiated, it will continue at high pressures with as little as 2 percent oxygen in steam while about 10 percent oxygen is required at atmospheric pressure.

The physical properties of titanium suggest that it would be more reactive in oxygen than other metals. This suggestion can be based on the following observed behavior of titanium:

a. Its low thermal conductivity and low heat capacity on a volume basis resulting in a low energy loss for any given energy input.

b. Its low ignition temperature in an oxygen environment.

c. A reactivity in high pressure oxygen at and above room temperature.

Titanium alloys subjected to high velocity impact will burn in a pure oxygen environment with pressures in the range of 20 to 60 psi, but will not burn in a pure nitrogen or a sea-level environment. This was experimentally proved with test cylinders 26

and 42 (Figures 25 and 26). Both diaphragms used in Experiment 26 were 0.016-inch sheets of 6Al-4V-Ti that were pressurized to 60 psi with gaseous nitrogen. The 0.097-gram projectile struck the front diaphragm with an impact velocity of 12,200 ft/sec and fragments of the projectile and diaphragm penetrated the rear diaphragm. There was no evidence of burning or detonation. Both diaphragms used in Experiment 42 were 0.016-inch sheets of 6Al-4V-Ti that were unpressurized and struck with the 0.097-gram projectile traveling at 12,200 ft/sec. Both diaphragms were penetrated with no burning or detonation.

Nitrogen will react with hot (800°C) titanium metal. However, the heat evolved (73.0 kcal/mole) with the formation of the nitride, from pure nitrogen at 60 psi, and titanium structures at ambient temperature struck with a high velocity projectile, is not sufficient to sustain the chemical reaction. Consequently, titanium structures pressurized with gaseous nitrogen will not react when subjected to impact with a hypervelocity projectile. Oxygen will react with hot (610°C) titanium metal. The heat evolved (218 kcal/mole) with the formation of the oxide, from pure gaseous or liquid oxygen at 60 psi and titanium structures at temperatures from 50° to -300°F. which are struck with a high velocity projectile, is sufficient to sustain the chemical reaction. Unpressurized titanium structures struck with a high velocity projectile in the sea level environment will not burn even with the 20 percent oxygen. This lack of reactivity can be attributed to the large concentration of nitrogen which effectively prevents the oxygen from reacting with titanium to form titanium dioxide. Consequently, not enough heat is generated to raise the energy of the titanium to the reaction temperature threshold necessary for the reaction to become self-sustaining (the reaction temperature threshold is the minimum temperature required to permit the metal to react spontaneously, and for the reaction to sustain itself).

The chemical reactivity between titanium structures at ambient temperature, and gaseous oxygen (60 psi), can be diminished by providing a layer of WD-40 between the reactants. The mechanism whereby the WD-40 functions as an inhibitor to the chemical reaction cannot be stated, although it may be postulated that the organic material, 1) wets the titanium metal, 2) prevents the gaseous oxygen from contacting the titanium, and 3) upon impact with the high velocity projectile, burns in the oxygen environment to form carbon oxides which reduces the oxygen concentration at the reaction zone and/or forms a boundary layer between the titanium and oxygen. In any instance, the oxygen pressure and environment is lost from the system, before the energy of the titanium can be raised to the reaction temperature threshold necessary for the reaction to sustain itself. The oxygen concentration in the sea-level environment is not high enough for the reaction to sustain itself, and the metal does not burn. This proposed mechanism cannot be applied to liquid oxygen systems, since the temperature of the structure is -297.4°F. At this temperature, the WD-40 coating may be brittle and flake-off or spall from the titanium metal upon impact with the high velocity projectile. The flaking-off of the WD-40 coating from the metal must be instantaneous with the impact, and the protective layer is removed so that oxygen contacts the metal and raises the energy of the titanium to the reaction temperature

threshold necessary for the reaction to sustain itself. In this instance, the titanium will burn as long as a critical oxygen concentration is maintained. The gaseous oxygen supplied for the reaction will be provided from the vaporization of liquid oxygen.

Structures fabricated from either full hard stainless steel 301 or aluminum 2024-T3 and pressurized with liquid or gaseous oxygen will not chemically react when struck and penetrated with a high velocity projectile under the conditions used in these experiments. It should be observed that higher velocity particles of very small mass may pierce structures and result in catastrophic damage. However, if either metal is in contact with a titanium alloy (6Al-4V-Ti or 5Al-2.5Sn-Ti) that is exposed to a high concentration of oxygen at the instant of hypervelocity impact then the chemical reaction will be catastrophic. This behavior can be attributed to the reactivity of the titanium alloy which burns in the oxygen environment and raises, due to its proximity, the temperature of the stainless steel or aluminum metal to the melting and/or kindling temperature. The energy from the exothermic reaction between titanium and oxygen is sufficient to maintain the temperature of either stainless steel or aluminum metal, at or above their reaction threshold temperature. It can be stated that titanium and its alloys should not be used in the construction of systems that contain oxygen or other oxidizing agents. Moreover, titanium and its alloys should not contact oxygen pressurized systems fabricated from stainless steel and aluminum. This reactivity between titanium and oxygen will necessitate careful design in all systems where titanium is used.

In addition to the hazards resulting from structures burning in the oxygen environment, there also is the possibility of explosive decompression. Even though stainless steel and aluminum structures pressurized with oxygen will not burn when struck with a hypervelocity particle, these structures may explode. Explosions of pressurized structures will occur when a crack or perforated area is formed, and this crack propagates catastrophically under the 60-psi internal pressure. Since almost all pressurized structures were pierced, and only three were observed to explode, it can be concluded that a critical crack length is necessary to permit the crack to propagate and result in an explosion (explosions probably resulted from more than three experiments, but the jagged fracture was destroyed by the burning of the metal in the oxygen environment. Penetration of the diaphragm(s) was made in a manner so that it was not simply pierced but was ripped). It should be recognized that a very small mass (0.001-gram) projectile at high velocity (75,000 ft/sec) may, 1) behave in a similar manner as a large mass (0.097-gram) projectile at a velocity of about 13,000 ft/sec and 2) produce an explosion in a pressurized structure. This point must be experimentally verified.

Several liquid pressurized cylinders were completely pierced. The first diaphragm was penetrated with no further damage, while the rear diaphragm was not only penetrated but was ripped apart by an explosion. This can be explained by the fact that the high velocity projectile, 1) initiates a compression wave in the metal cylinder as a result of impact on the front diaphragm, 2) passes through the media with a

velocity in excess of the sonic velocity of the media, 3) initiates a shock wave in the media which trails the projectile, and 4) pierces the rear diaphragm and thereby weakens the metal so that the structure ruptures, since it cannot reflect the onrushing, high strength compression wave. It can be concluded therefore, that the front diaphragm will rupture and release the pressure when the projectile impacts the structure so that a crack of some minimum length is formed; the front diaphragm will be pierced while the rear diaphragm will rupture and release the pressure, when the strength of the shock wave set-up in the liquid media is great enough to rip the metal structure, weakened by penetration from the projectile and spall fragments.

Three experiments (7, 25, and 46) were made to prove that the pressurized cylinder would not rupture when subjected to a shock wave generated by an explosive charge. The one pound charge was detonated at a distance of 4-1/2 feet from the structure with no adverse effect; i.e., loss of pressure. It should be observed, however, that the force of the shock wave was partially diminished by the blast shields (Figure 2).

4.3 CONCLUSIONS. Based upon the results found in this experimental program as well as those reported in the literature (Reference 3), the following statements can be made with regard to the reaction between titanium and oxygen:

a. Explosions that occur in liquid oxygen systems subjected to hypervelocity impact result from the shock wave generated by the impact and/or the reactions that take place in gaseous oxygen.

b. Chemical reactions will occur in gaseous oxygen, but very few take place at the temperature of liquid oxygen. Oxygen is relatively inert in the liquid state; i.e., a cold iron wire immersed in liquid oxygen does not react; a hot wire is quenched; and only a burning iron wire will continue to burn and explode.

c. Gaseous oxygen is generated from liquid oxygen by the heat released from the impact of a high velocity particle. Not to be overlooked is the rapid evaporation rate of liquid oxygen.

d. Titanium will react with oxygen under dynamic conditions with pressure as low as 50 psi (Figure 27), if the oxygen concentration is at 35 percent, the minimum level necessary for reaction to occur. The reaction sustains itself when a fresh titanium surface is exposed to the oxygen, and the oxidation rate is dependent on both the oxygen pressure and concentration. When the oxidation rate is high and the heat is generated faster than can be lost to the surroundings, then the temperature of the metal increases until it melts. When melting occurs, the reaction becomes self sustaining and continues until either one of the reactants is consumed. This reactivity can be attributed to the solubility and rapid diffusivity of the titanium oxides in liquid titanium, which provides a fresh molten surface to react with the oxygen. Zirconium, whose oxide is soluble in the molten metal,

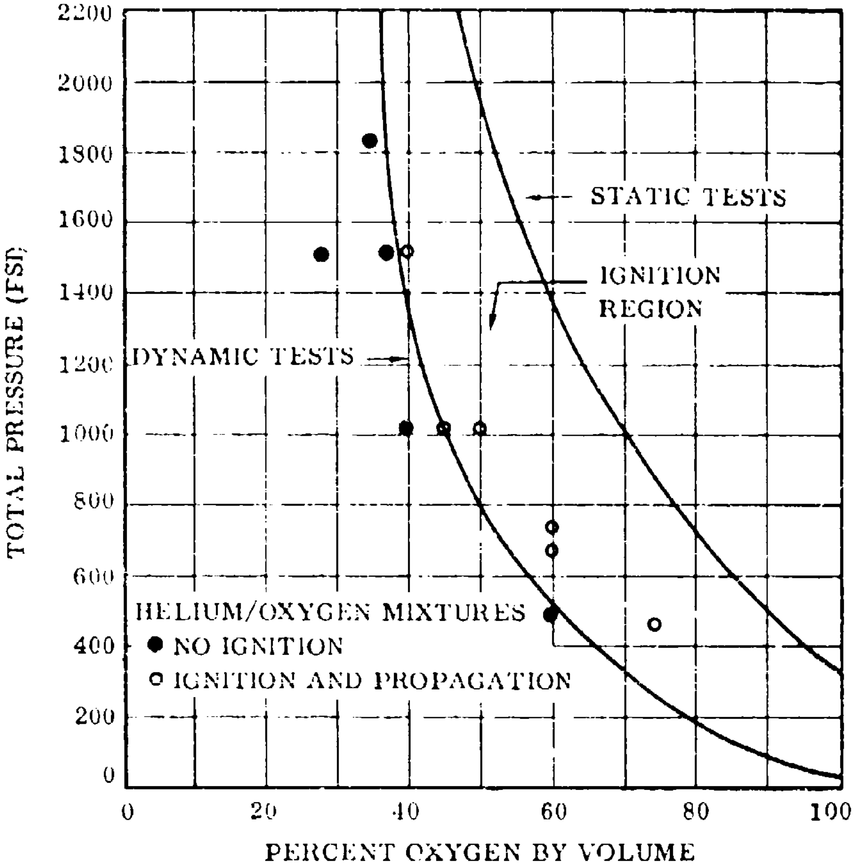


Figure 27. Reactions of Titanium With Helium/Oxygen Mixtures (Dynamic Tests)

and aluminum, magnesium, tantalum and columbium, whose oxides are insoluble, have been tested and only zirconium burned.

It appears that the solubility of the oxide in the metal is the most important factor in permitting deflagration. However, the protective film concept should not be completely disregarded. It should be observed that high gas flow rates may remove protective oxide films, cause the film to move or flow over the molten metal and thereby produce a clean metal surface for reaction to occur.

APPENDIX

Test Cylinder. The five-inch diameter test cylinder was fabricated from 1/2-inch thick stainless steel and the details of construction are given in Figures 28 and 29 and Table 5. A 3/8-inch thick flange, provided with a Toruseal groove (0.25-inch by 0.075-inch) for sealing, was welded on each end of the cylinder. The two 7-inch diameter test diaphragms were placed between the cylinder and mating flanges held in place with twelve 1/4-inch bolts. This cylinder was purged for 3 to 5 minutes with gaseous nitrogen, and 5 minutes with gaseous oxygen before the tank was pressurized for impact testing. Purging and overflow was accomplished by opening the 1-inch line located on the top of the cylinder, while the 1/2-inch line located on the side of the cylinder was used to fill the tank.

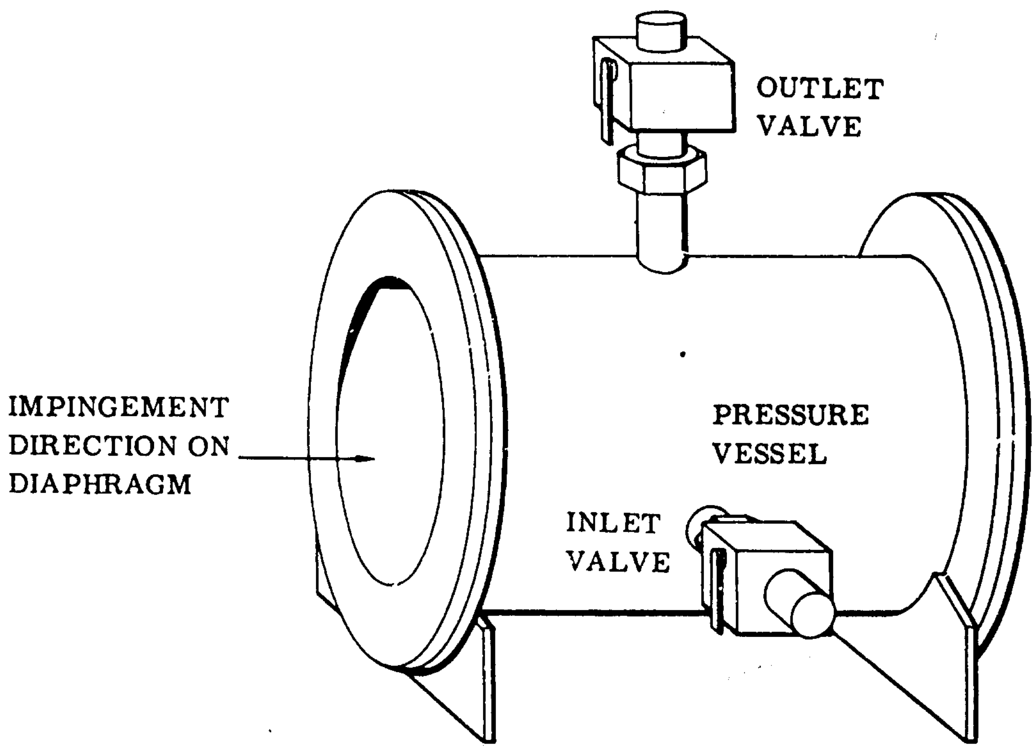
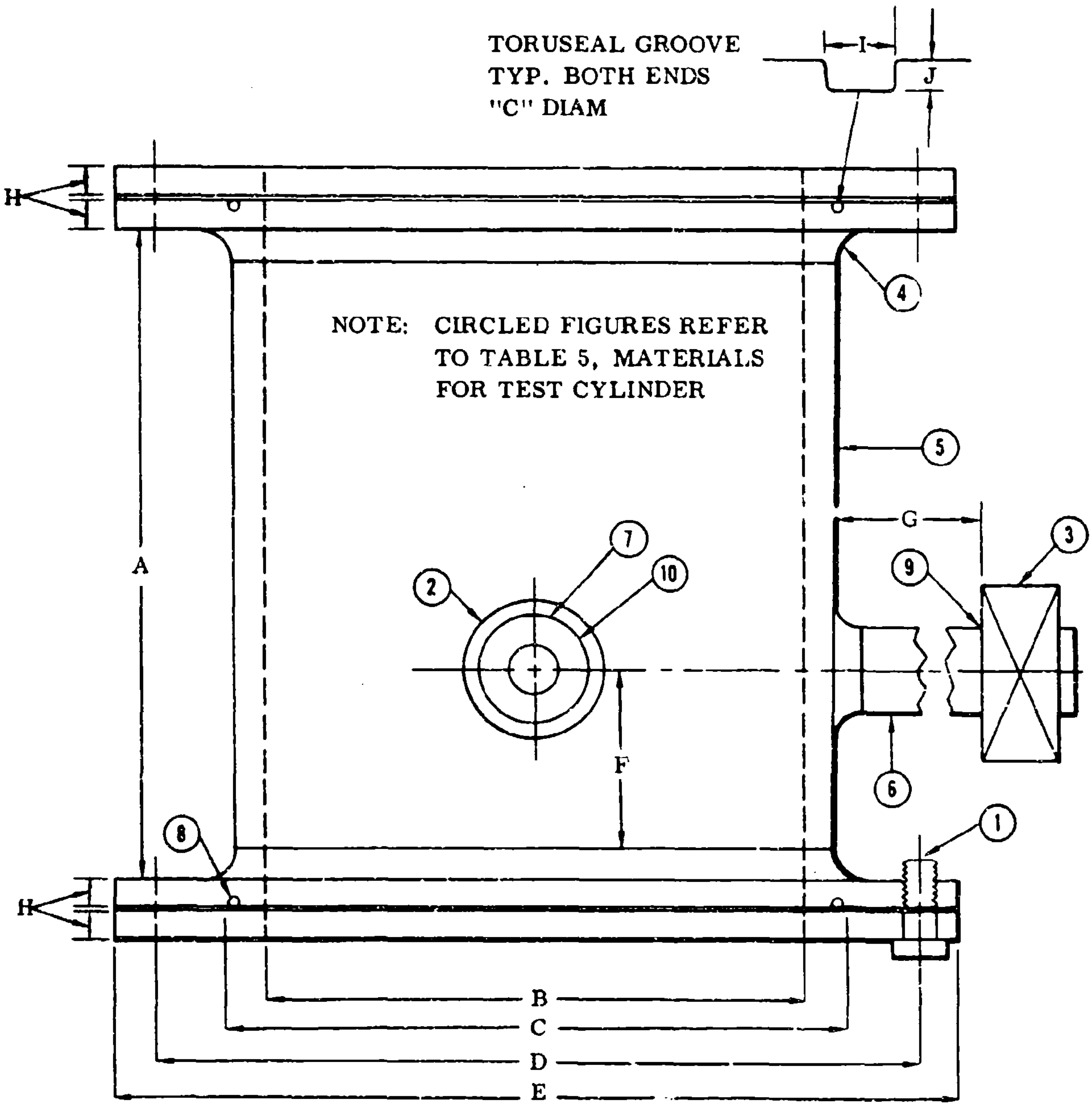


Figure 28. Pressurized Test Cylinder and Fixture



A	B	C	D	E	F	G	H	I	J
6.0	5.0	5.755 5.760	6 1/8	7.0	3.0	6.0	0.375	0.250	0.075 0.080

Figure 29. Construction Details of the Test Cylinder

Table 5. Materials for Test Cylinder

ITEM	MATERIAL DETAILS AND INSTRUCTIONS
1.	Twelve hex head cap screws, 1/4 NF 28, A286, 3/4 in. long. Typical for both ends of test cylinder.
2.	Manually operated Flo-Ball valve, Hydromatics Inc., Model 115C stainless steel for liquid-oxygen service, 1/2-inch nominal size. Valves 2 and 3 are positioned 90 degrees apart 8 inches from tank.
3.	Manually operated Flo-Ball valve, Hydromatics Inc., Model 115F stainless steel for liquid-oxygen service, 1-inch nominal size.
4.	Weld flange rings to pipe. Machine flange surface after welding.
5.	Stainless steel pipe, 5-inch nominal size.
6.	1-inch stainless steel fitting and 10056-16. Weld to Tank. Use stainless steel flare nuts and 8 inches of Type 304 tubing.
7.	1/2-inch stainless steel fitting and 10056-8. Weld to Tank. Use stainless steel flare nuts and 8 inches of Type 304 tubing.
8.	Stainless steel Toruseal, Size No. C5750A. Typical for both ends of test cylinder.
9.	1-inch stainless steel flare nut on 8-inch length of Type 304 tubing to fit and 10056-16 on valve.
10.	1/2-inch stainless steel flare nut on 8-inch length of Type 304 tubing to fit and 10056-8 on valve.

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